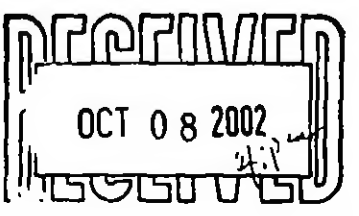
PART I
FINAL CHAPTER

WSHJ WIND REPORT
JUNE 1966



WORTHINGTON, SKILLING, HELLE & JACKSON

Consulting Civil and Structural Engineers · 230 Park Avenue, New York, N. Y. 10017 · Mu. 9-8874

RESULTS OF AEROELASTIC TESTS ON THE TOWERS OF THE WORLD TRADE CENTER IN TURBULENT FLOW

General

Supplement Number 2 of the Wind Report includes a description of the wind tunnel models of The World Trade Center and contains a selection from the wind tunnel tests undertaken at Colorado State University. In that report results are presented of the steady pressure measurements and of the aeroelastic tests carried out on a single tower in uniform flow. Part of the purpose of these particular tests was to provide a comparison between the performance of the models used at the Colorado State University and those used at the National Physical Laboratory. This comparison led to the conclusion that the aerolastic tests performed at these two locations on the single tower in uniform flow were in good qualitative and quantitative agreement. Figs. 21 and 22 of this earlier supplement which was used to demonstrate this agreement is shown in Figs. 1 and 2.

NOTE: All references are listed by author and by year of publication at the end of this supplement.

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FIG. 1 COMPARISON OF PEAK LATERAL OSCILLATION AMPLITUDES FOR SINGLE TOWER IN STEADY UNIFORM FLOW DETERMINED FROM CSU AND NPL WIND TUNNEL TESTS (WIND NORMAL TO FACE)

———— CSU (WEAK AXIS)

– – – – NPL

$c/c_{crit.}$ = CRITICAL DAMPING RATIO

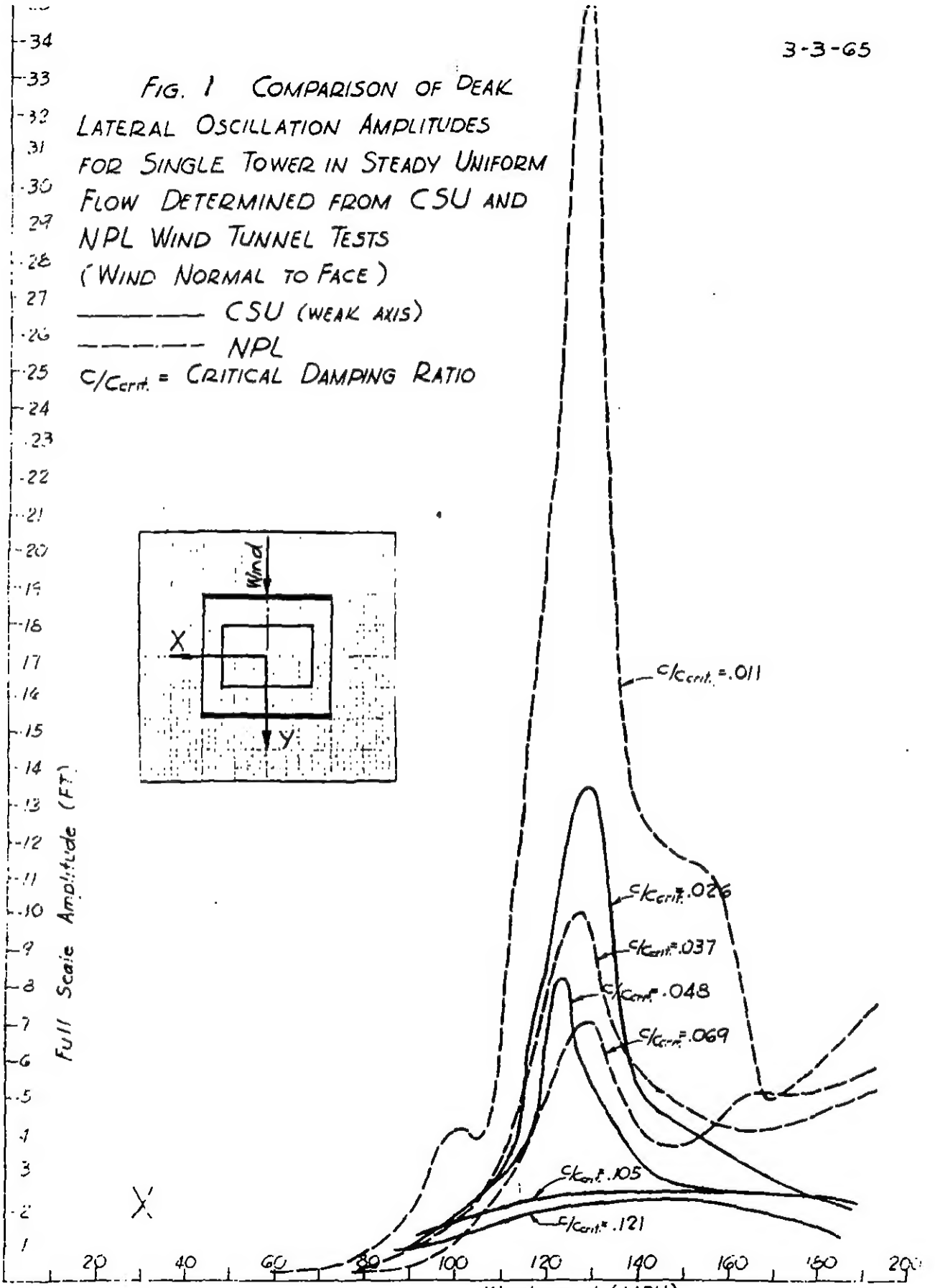

FIG. 1

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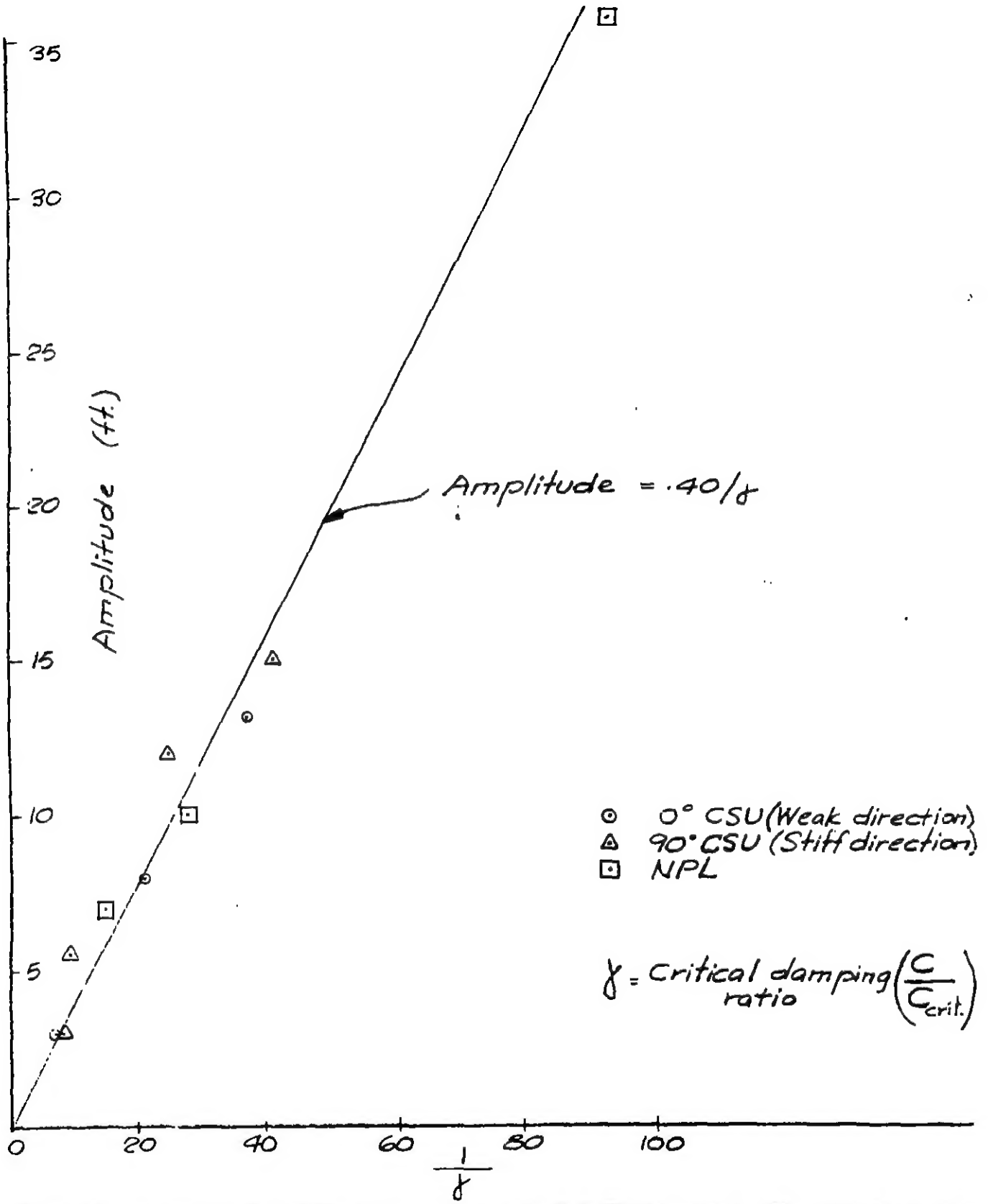

FIG. 2 COMPARISON OF OBSERVATIONS MADE AT CSU & NPL OF THE VARIATION OF PEAK AMPLITUDE OF OSCILLATION WITH DAMPING FOR A SINGLE TOWER IN UNIFORM FLOW

FIG. 2

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The purpose of Part I of this supplement is to report the results of the aeroelastic tests carried out at CSU in the realistic flow conditions represented by the turbulent boundary layer, both on the single tower and twin tower configuration. In addition, comparison is made with similar tests carried out at NPL in a turbulent shear flow generated by a grid and, in the discussion an explanation, a theoretical model for the results is advanced which, it is believed, accounts for the observed behaviour and, in certain instances, the differences in response between the two CSU flow conditions (New York Southeast and Southwest models) and the NPL tests.

The test series described in this report are given in Table I.

TABLE I

Tower Configuration	Wind Tunnel Establishment	Model Scales			Types of Flow
		Density	Time	Length	
Single	CSU	1	1/60	1/500	Turbulent boundary layer S.E. Model of New York
Single	CSU	1	1/200	1/500	Turbulent boundary layer S.W. Model of New York
Single	NPL	1	1/50	1/400	Turbulent shear flow *Isotropic turbulence*
Twin	CSU	1	1/60	1/500	Turbulent boundary layer S.E. Model of New York
Twin	CSU	1	1/200	1/500	Turbulent boundary layer S.W. Model of New York
Twin	NPL	1	1/50	1/400	Turbulent shear flow

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Photographs taken at CSU of the aeroelastic models and of the two models of New York are shown in Figs. 3 and 4.

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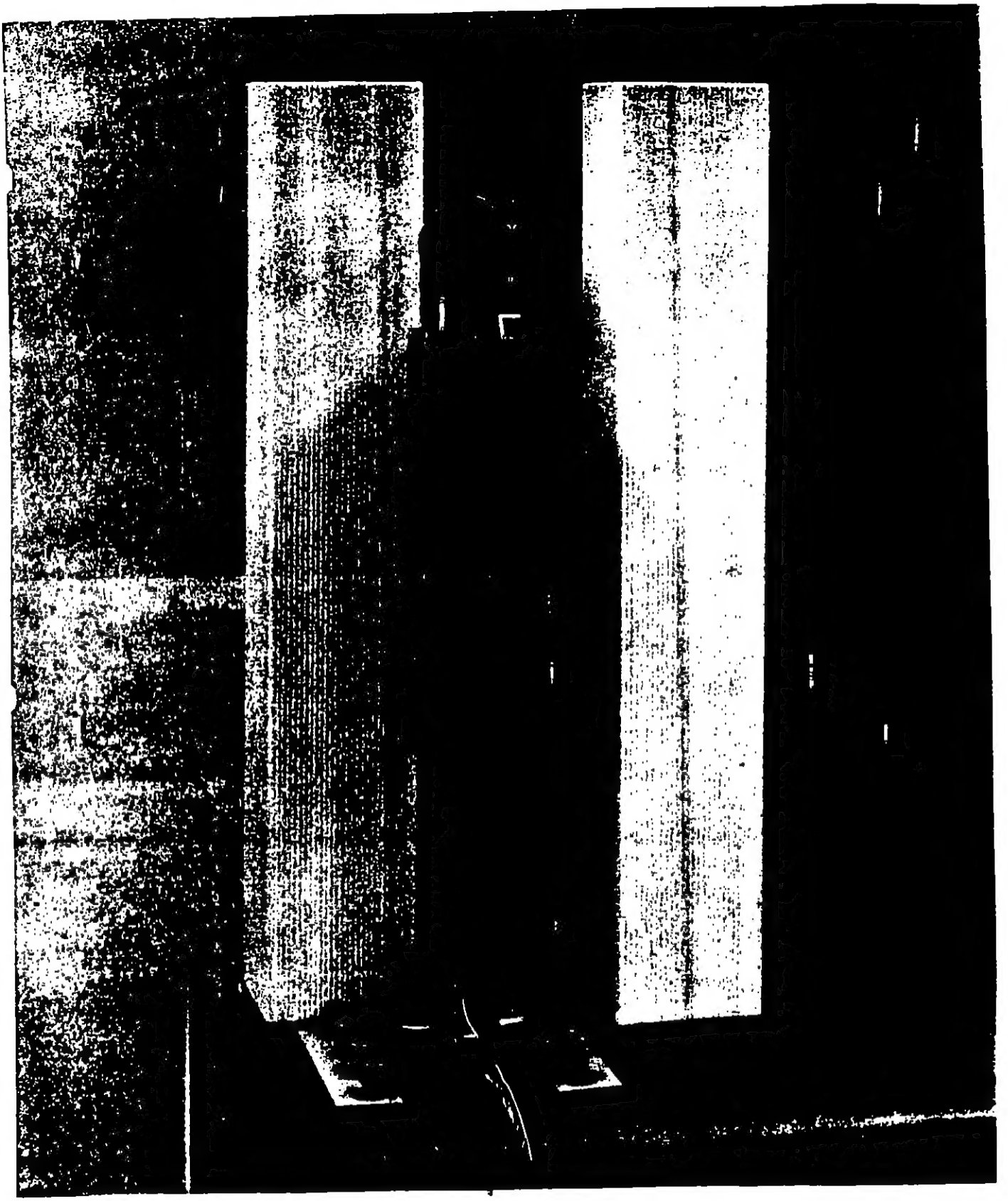

AEROELASTIC WIND TUNNEL MODELS AS USED AT COLORADO STATE UNIVERSITY

FIG. 3

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FIG. 4

VIEW FROM SOUTHWEST OF AEROELASTIC MODELS OF THE WORLD TRADE CENTER TOWERS MOUNTED IN THE WIND TUNNEL.

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Scaling of Models

Although the scaling of models has already been described in the NPL report and in Supplement No. 2 of the Wind Report, further comments are pertinent. It has been shown that similarity between the full scale and the model can be achieved if all significant parameters of the system, such as lengths, times and masses, are in the same ratio to one another on the model and on the full scale. That is:

$$L_{1_m} : L_{2_m} : L_{3_m} : - - - L_{N_m} = L_{1_p} : L_{2_p} : - - - L_{N_p}$$

$$T_{1_m} : T_{2_m} : T_{3_m} : - - - T_{N_m} = T_{1_p} : T_{2_p} : - - - T_{N_p}$$

$$M_{1_m} : M_{2_m} : M_{3_m} : - - - M_{N_m} = M_{1_p} : M_{2_p} : - - - M_{N_p}$$

where m and p stand for model and prototype and the suffixes $1, 2 - - - N$ refer to the set of N salient lengths, times and masses defining the properties of the system. It follows that all other parameters compounded of these physical dimensions such as forces (MLT^{-2}), and velocities (LT^{-1}) also are in the same ratio to one another on full scale and model. These similarity relationships can be expressed otherwise in terms of dimensionless ratios as described by Whitbread and Scruton in the NPL report (Part 1).

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The similarity relationships can be expressed in terms of the following basic requirements:

1. Geometric similarity between model and prototype
2. Similarity of the flow approaching the model both with regard to the mean flow distribution and the characteristic turbulence intensities and scales
3. $\left(\frac{V}{nL}\right)_m = \left(\frac{V}{nD}\right)_p$
4. $\gamma_m = \gamma_p$ and,
5. $\left(\frac{\rho D^5}{I}\right)_m = \left(\frac{\rho D^5}{I}\right)_p$

where

V is any velocity characteristic of the model and prototype;

n is any frequency characteristic of the model and prototype;

γ is the critical damping ratio;

ρ is the air density;

D is the diameter; and

I is the effective moment of inertia.

Geometric similarity was achieved by reducing all model lengths to 1/500 of the full scale length for the CSU model and 1/400 of the full scale length for the NPL model.

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To obtain similarities of turbulent boundary layer flows was more difficult since the governing requirements are still imperfectly understood. In fact, it should be noted that the tests on The World Trade Center were the first in which this had been seriously attempted.

It seemed intuitively that one way to achieve this was to model the mechanism by which turbulence is generated, namely by a shearing action at the surface. This approach was made possible in the CSU tunnel by the unusually long working section available. Jensen (1959) had shown that, by producing a surface of equivalent aerodynamic roughness in the wind tunnel, the mean flow gradient was correctly reproduced. The aerodynamic roughness is governed by the roughness length of the surface and equivalence is obtained by scaling this length in accordance with the general length scaling employed.

Other factors such as the boundary layer thickness, the characteristic rate of dissipation of energy are also likely to affect the scale of the turbulence, but in an undetermined manner. To overcome this difficulty, the boundary layer thickness was controlled by the extent of the upstream roughness so as to correspond approximately to the effective boundary layer thickness to be found in the atmosphere. As a further check, two sets of mounts were built for the aeroelastic models so as to vary the frequency of the models and thus the time scaling. This precautionary measure was later proven to be unnecessary as no sensitivity on time scaling was found.

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In the NPL tunnel, the alternative approach to generating a turbulent boundary layer was taken, namely by adjusting the upstream flow by a grid of bars. This produced a flow having representative mean flow characteristics of average conditions at the site of The World Trade Center and certain turbulence characteristics of approximately the correct magnitude.

The reduced velocity $\frac{V}{nD}$ and the damping ratio β were treated as variables; the former by varying the wind velocity used in the tests and the latter by adjusting the eddy current damping unit.

The fifth criterion, equivalence of the density ratio $\frac{I}{\rho D^5}$, was not treated as a variable and some discussion of its influence is necessary. Small changes in density of the building have occurred during the progress of design and differences exist in air density between that occurring in the wind tunnel and that which the meteorological study has shown to be pertinent to the design of The World Trade Center towers.

A comparison of the values used in testing with the full scale values is given in Table 2.

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TABLE 2

Structure	D ft.	I slug/ft.^{2}	ρ slug/ft.^{3}	$\frac{\rho D^5}{I} \times 10^4$
Full Scale - May 1964	208	11.4×10^{12}	.0023	.786
CSU Model 1/500 Scale (as tested)	.42	.364	.0019	.650
NPL Model 1/500 Scale (as tested)	.52	1.110	.00238	.812
Full Scale - March 1966	208	10.4×10^{12}	.0023	.859

For the CSU tests, it is noted that the value of the density ratio $\frac{\rho D^5}{I}$ is some 20% less than that used at NPL and 30% less than that anticipated for the final design. This is principally due to the air density in the Colorado State University wind tunnel being less than anticipated.

Some variation in the density factor between the model and the full scale was almost inevitable owing to variations in the effective moment of inertia of the building as design progressed and to the uncertainty surrounding the value of the air density appropriate for the final design of the building. Some reliance on theory had to be made to make this adjustment. It is shown in the discussion and in the paper by Davenport (1966) that for a relatively

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lightly damped structure the response of the structure to a turbulent air stream can be represented by the relationship

$$\text{Amplitude of response} \propto \left(\frac{e D^5}{I}\right) \frac{1}{\sqrt{\gamma + \gamma_{aero}}} \left(\frac{V}{nD}\right)^2 \cdot f\left(\frac{V}{nD}\right)$$

where γ_{aero} is the aerodynamic damping induced by the motion of the structure through the air.

It is shown in the discussion that at higher wind velocities the aerodynamic damping can be approximated by the expression

$$\gamma_{aero} \propto \left(\frac{e D^5}{I}\right)\left(\frac{V}{nD}\right)$$

and thus is proportional to the density ratio and the wind velocity. Preliminary estimates indicated that with values of structural damping γ of 2 percent of critical and greater and for wind velocities in the range from 100 to 125 mph, γ_{aero} was appreciably less than γ. This is the range of wind speeds of special significance in the structural design. At higher wind speeds, in the range 150 mph and greater, this assumption is not necessarily valid.

As shown by the foregoing discussion, over the range of wind speeds below 125 mph and for damping values $\gamma > .02$.,

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$$\text{Amplitude} \propto \left(\frac{e^{D^5}}{I} \right) \quad \text{(approximately)}$$

For purpose of comparing responses, therefore, all amplitudes measured on the CSU model were increased initially by 20 percent to correspond to the density ratio of .786. Later in the design, further adjustments in the response were made to correspond to the final density ratio of the towers. This last correction is described in Part III of this supplement.

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Definition of Model Configuration

Unless otherwise specifically stated, all results in this report refer to a full scale density ratio $\frac{\rho D^5}{I}$ of .79 and to towers having the frequencies given in Table 3.

TABLE 3

Tower	Direction of Oscillation	Frequency
A	N-S	.096 cps.
A	E-W	.084 cps.
B	N-S	.084 cps.
B	E-W	.096 cps.

All azimuth angles in the wind tunnel tests (unless specifically noted) refer to a north-south line parallel to the tower axes. Meteorological studies refer to true north. This relationship is amplified in Figure 5.

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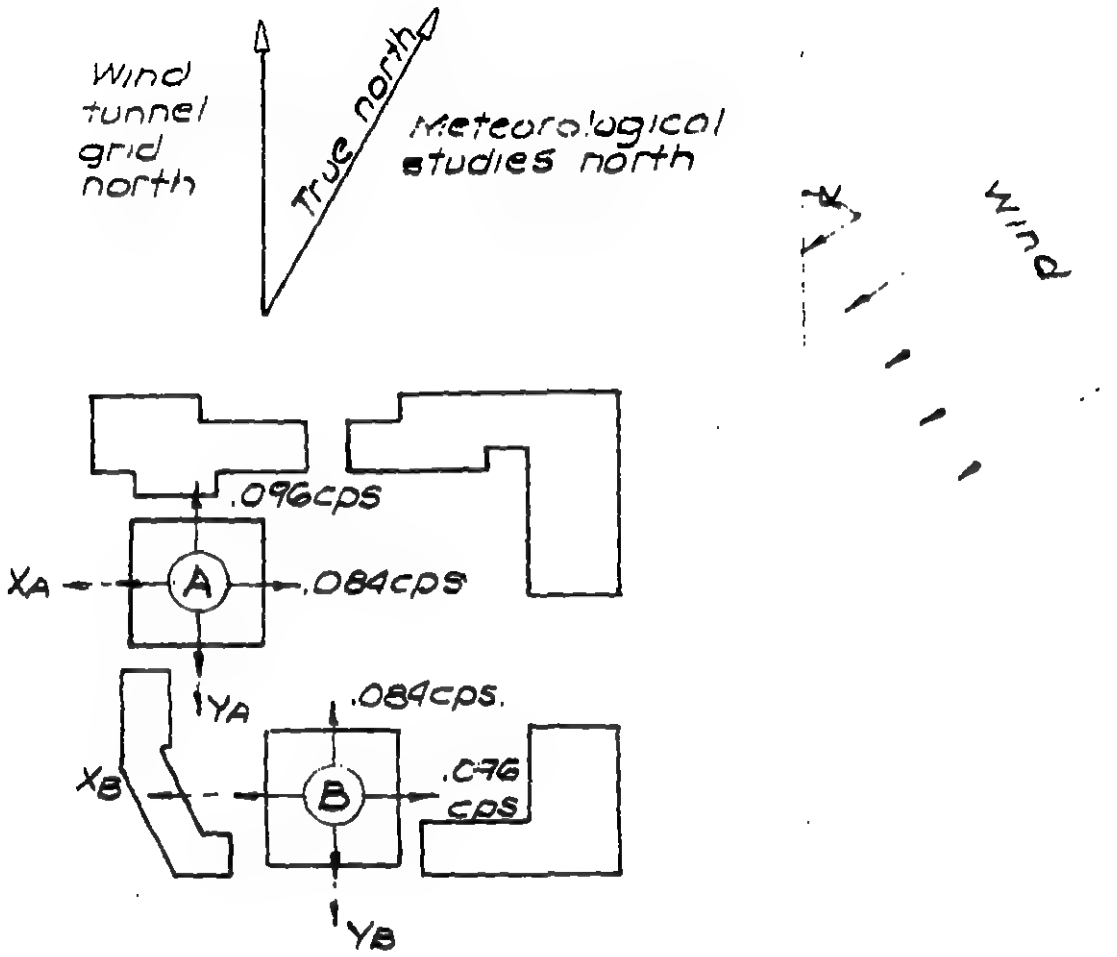

DEFINITION OF GRID SYSTEM AND TOWER CONFIGURATIONS

FIG. 5

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Test Procedure

The test procedure used in the aeroelastic tests at CSU are described in Supplement #2. To recapitulate, continuous records of the deflection response of each tower in each direction were obtained on a Sanborn strip chart recorder. The simultaneous velocity pressure obtained from the pitot tube mounted upstream of the tower model at the center line of the tunnel (equivalent to 1500 ft. above the base of the tower) was also recorded. Readings were made throughout ranges of wind velocities corresponding to 0 - 200 miles/hour in the case of the low frequency models and 0 - 140 mph in the case of the high frequency models. During the tests, the velocity was usually kept steady for periods corresponding to approximately 20 minutes full scale to allow steady state conditions to be established before the velocity was increased to a higher value. Models were tested at approximately every 15° of azimuth, although in some instances intervals of 30° and 5° were used as conditions warranted. Typical chart traces are shown in Figs. 6, 7 and 8. Fig. 6 shows a test with a single tower while Figs. 7 and 8 show tests with towers present. These tests are discussed in greater detail below.

Prior to each test series, the damping current in the eddy current units was fixed and then a damping decay curve of each model was recorded on the chart. Values of damping were estimated from this set of curves rather than from the current meter.

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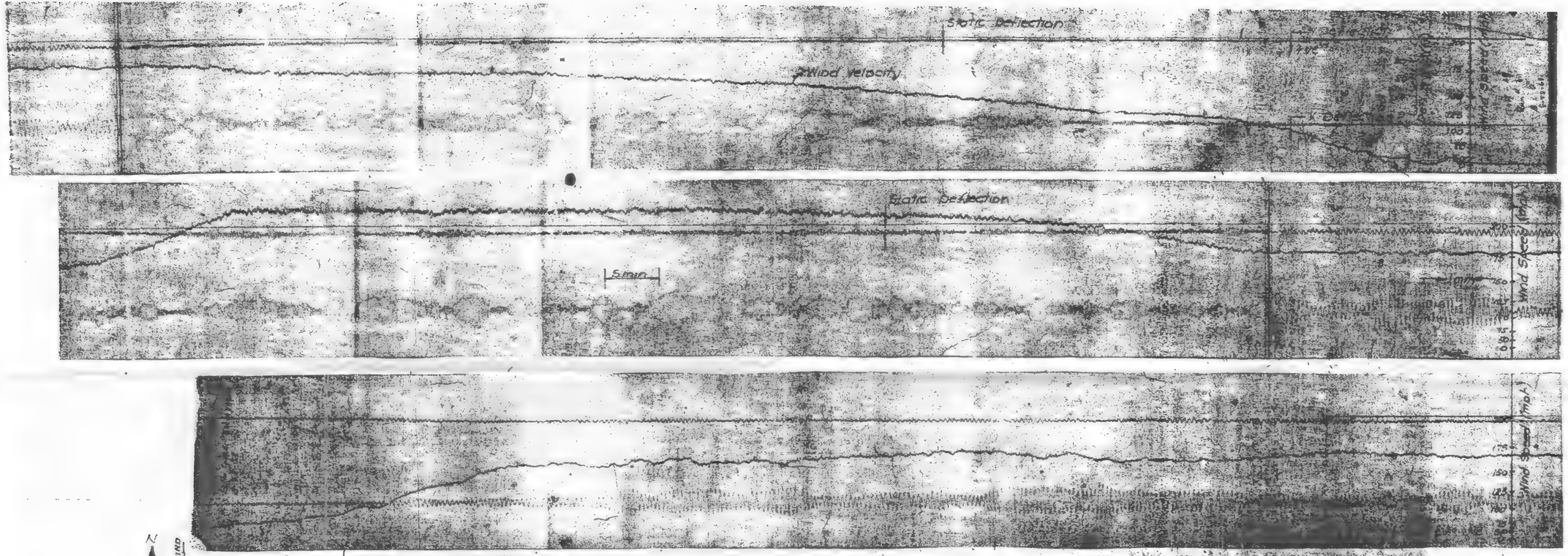
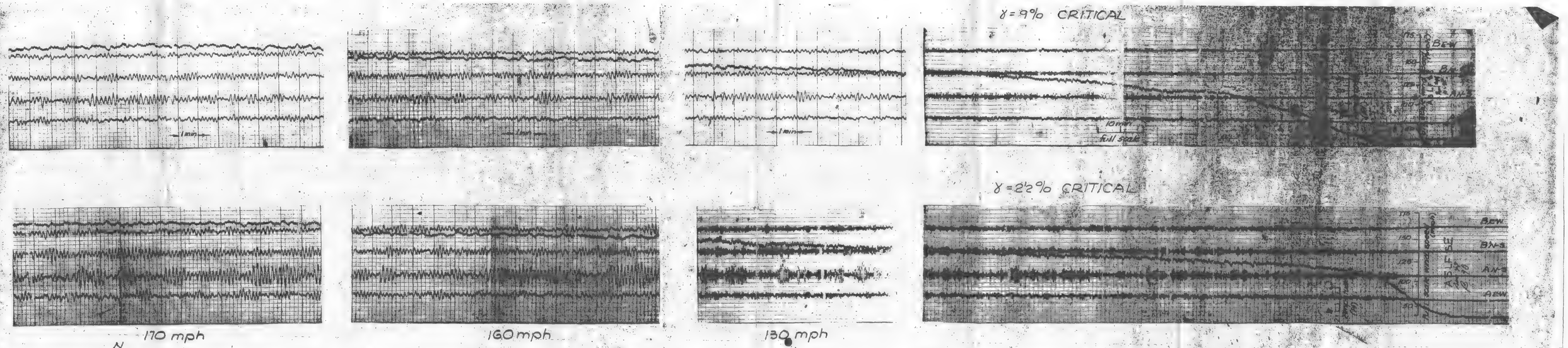


TYPICAL CHART RECORD OF RESPONSE OF SINGLE TOWER TO TURBULANT FLOW WITH SOUTH EAST MODEL OF NEW YORK



COMPARISON OF THE RESPONSE OF TWIN TOWERS TO TWO LEVELS OF DAMPING IN TURBULENT BOUNDARY LAYER (SE MODEL OF NEW YORK $\alpha = 90°$)

FIG. 7

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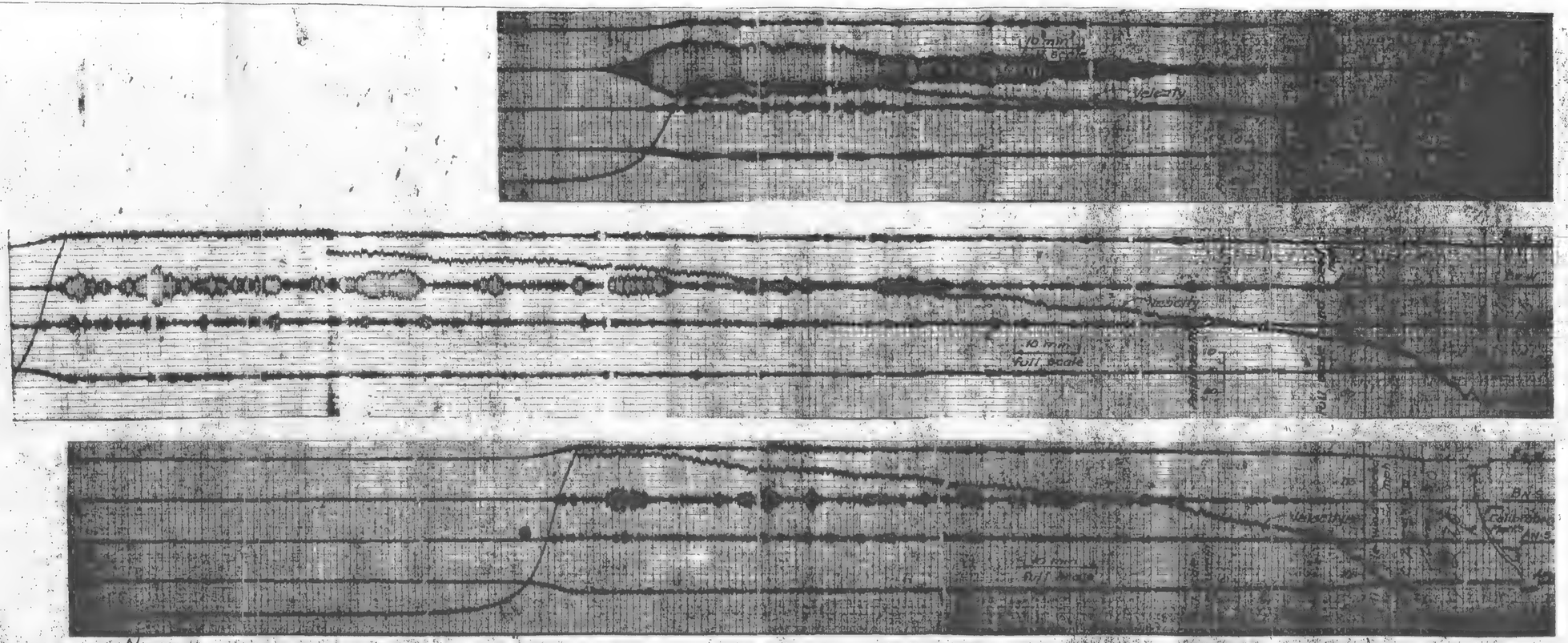

COMPARISON OF THE RESPONSE OF TWIN TOWERS TO TURBULENT BOUNDARY LAYER AT THREE LEVELS OF DAMPING (δ)
(SW MODEL OF NEW YORK $\alpha = 270°$)

FIG 8

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From the chart traces, preliminary plots were made of peak amplitude versus wind velocity for each degree of damping and for each orientation of the building. Since the damping was not necessarily precisely the same for all tests, these preliminary curves at various levels of damping were later interpolated to give estimates of amplitude at even values of damping. For the most part, damping values of 1%, 2%, 5%, 10% and 20% were used for this purpose.

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Response of Single Tower

The dynamic response of the single tower was found to have significant dependence on all of the variables considered, namely, the wind velocity, the orientation of the model, the degree of damping and the nature of the flow.

For the single tower the findings of the CSU tests are summarized in Figs. 9 through 13. Some of the chart traces corresponding to the results in Fig. 9 are given in Fig. 6. The corresponding NPL tests for the single tower are summarized in Figs. 11 through 15 of the NPL report of July 1965.

Fig. 9 compares the response of the tower to three flow conditions studied at CSU, namely, the smooth uniform flow and the two turbulent boundary layer flows with the southwest and southeast models of New York. (Reference to Fig. 8, 17, 22 and 31 of Supplement #1 to this Wind Report shows that the southeast model gives rise to a considerably more turbulent air flow and more pronounced gradient of mean wind speed than does the southwest model). Figs. 10 through 13 shows in greater detail the variations in response of the towers with wind direction and with degree of damping. In a number of instances logarithmic scales are used; this is to give greater emphasis to the lower amplitudes of oscillation which are associated with the comfort aspects of design at moderate wind speeds. This presentation on logarithmic scales also reveals any power law relationships between velocity and amplitude which might be present and which are then indicated by straight line relationships.

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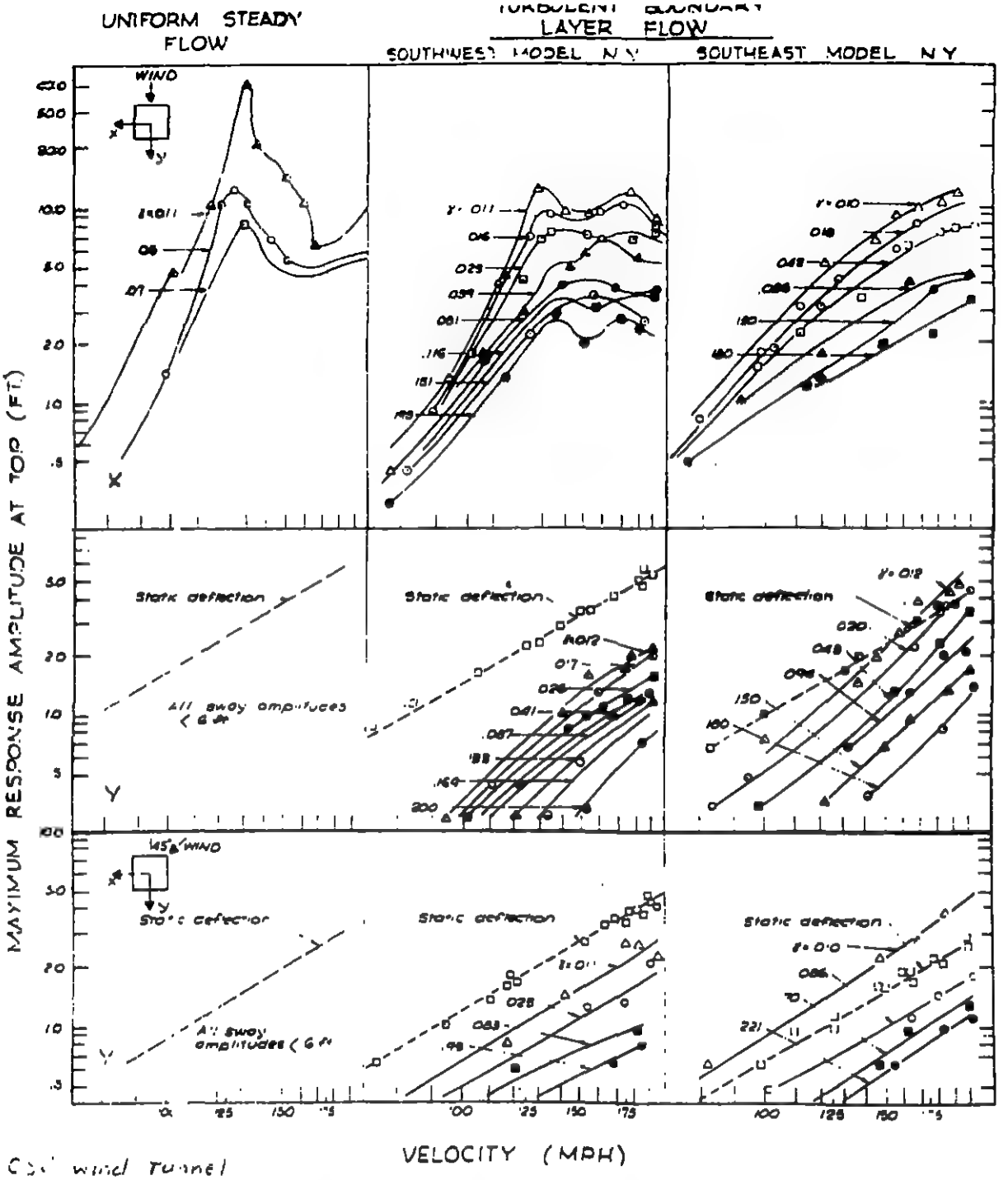

FIG 9 COMPARISON OF DYNAMIC AND STATIC RESPONSE OF SQUARE TOWER (H=650) TO UNIFORM STEADY FLOW AND TO TURBULENT BOUNDARY LAYER FLOW FOR VARIOUS CRITICAL DAMPING RATIOS

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FIG 10

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

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FIG 11

VARIATION OF MAXIMUM SWAY AMPLITUDE
WITH WIND DIRECTION AND DEGREE OF DAMPING

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FIG 12

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

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FIG 13

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

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Examination of the results of tests on the single tower suggest the following conclusions:

1. Both CSU and NPL results indicate that the most severe oscillations of the single tower are transverse to the wind and occur with the wind blowing within a small range of angles on either side of the normal to a face. (Figs. 10-14).
2. In uniform flow these transverse oscillations are largest for a critical range of velocities, and are characteristic of vortex shedding. In extremely turbulent boundary layer flow (southeast model of New York) Fig. 9 shows the response is not peaked but increases monotonically with increase in wind velocity. (This is also true of the NPL tests showing in Figs. 13 and 15 of the NPL report). The response in the moderately turbulent southwest model of New York is intermediate and still retains indications of a peaked response at the critical velocity for the uniform flow. Increase in turbulence level, therefore, appears to suppress vortex shedding excitation but gives rise to turbulence excitation which increases with wind speed.
3. Fig. 9 shows that the longitudinal oscillation with the wind blowing normal to a face and the oscillations in the 45° wind are negligibly small in uniform flow but not in boundary layer flow. The response amplitude appears to depend on the turbulence level in the boundary layer. The response increases monotonically with mean wind velocity at a rate approximately proportional to V^2 or V^3.

4. The steady component of the response for both the normal wind and the wind at 45° vary with V^2 (as is to be expected). The more pronounced are the boundary layer characteristics, the smaller the steady component of the response.

5. The effect of damping is, in all cases, to reduce the dynamic response. In the uniform flow an increase in damping produces a greater proportional reduction in amplitude compared to turbulent flow.

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Response of Twin Towers

The results of the aeroelastic model tests with twin towers in turbulent boundary layer flow carried out in the CSU and NPL wind tunnels are given in Figs. 14-29. These graphs give the peak amplitudes of oscillation as a function of wind direction at the stated wind velocities for several degrees of damping. They are arranged in sets of four corresponding to the two directions of oscillations of the two towers. Results are given for a range of wind velocities. As noted earlier, the amplitudes given for the CSU tests have been increased by 20% over the measured amplitudes to compensate the lower air density/building density ratio used in the tests.

The NPL results have been plotted from the original set of curves supplied by the laboratory. Tests carried out at NPL covered large amplitude oscillations only from 0° - 180°; to estimate the amplitudes for the reciprocal wind directions it was assumed that the coupling effects were negligible and that the response amplitude depended only on the reduced velocity applicable to the motion $\frac{V}{n_1 D}$ -- where V is the velocity, n_1 is the natural frequency of the mode of oscillation and D is the diameter. The amplitude of oscillation of the towers for angles greater than 180° and for a velocity V_1 was then found from the amplitude of the opposite towers at the reciprocal angle and at the velocity $V_1 \frac{n_2}{n_1}$; the ratio $\frac{n_2}{n}$ represents the ratio of the frequency in the mode whose amplitude is required to the frequency about the parallel axis of the other tower.

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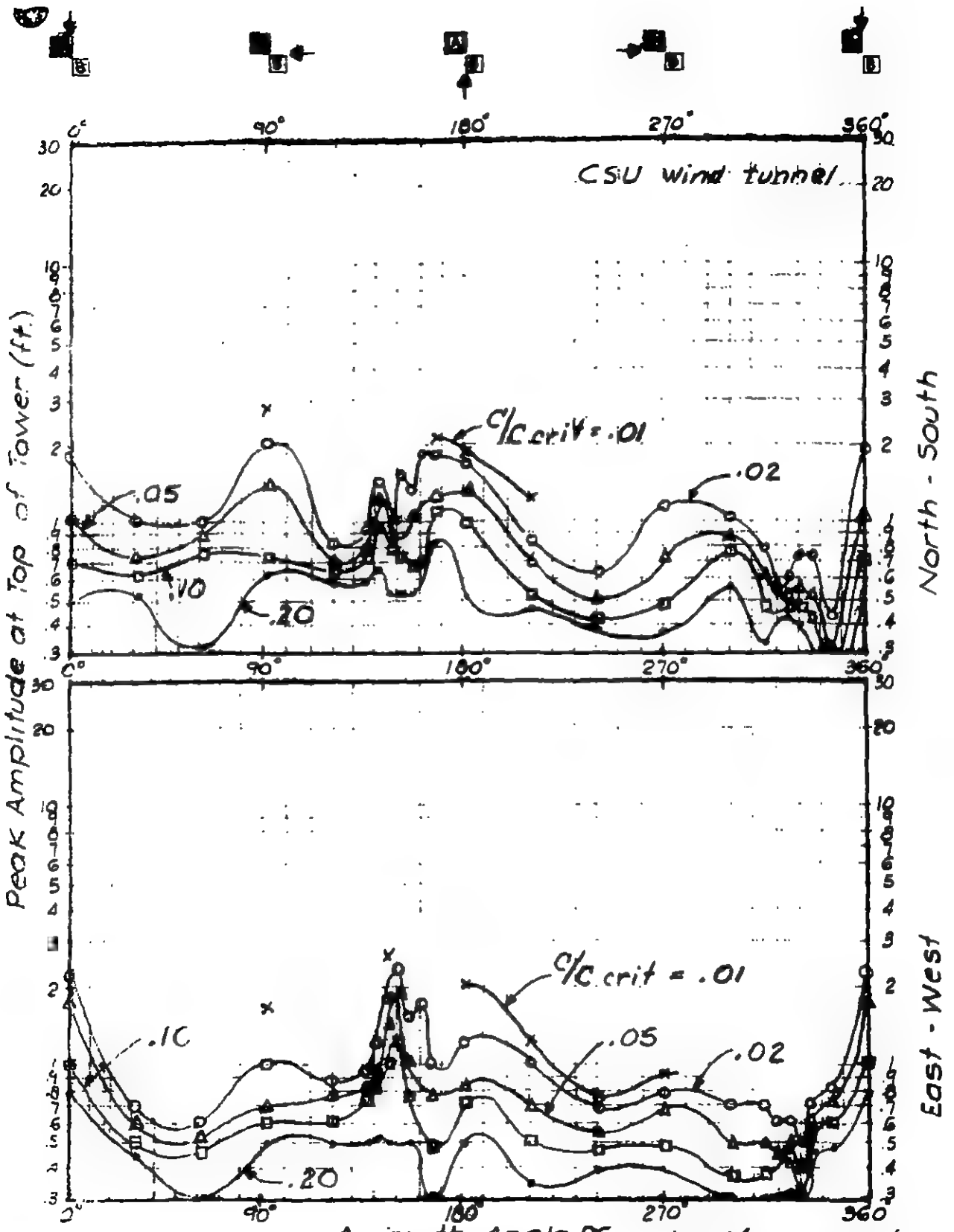

TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 14a

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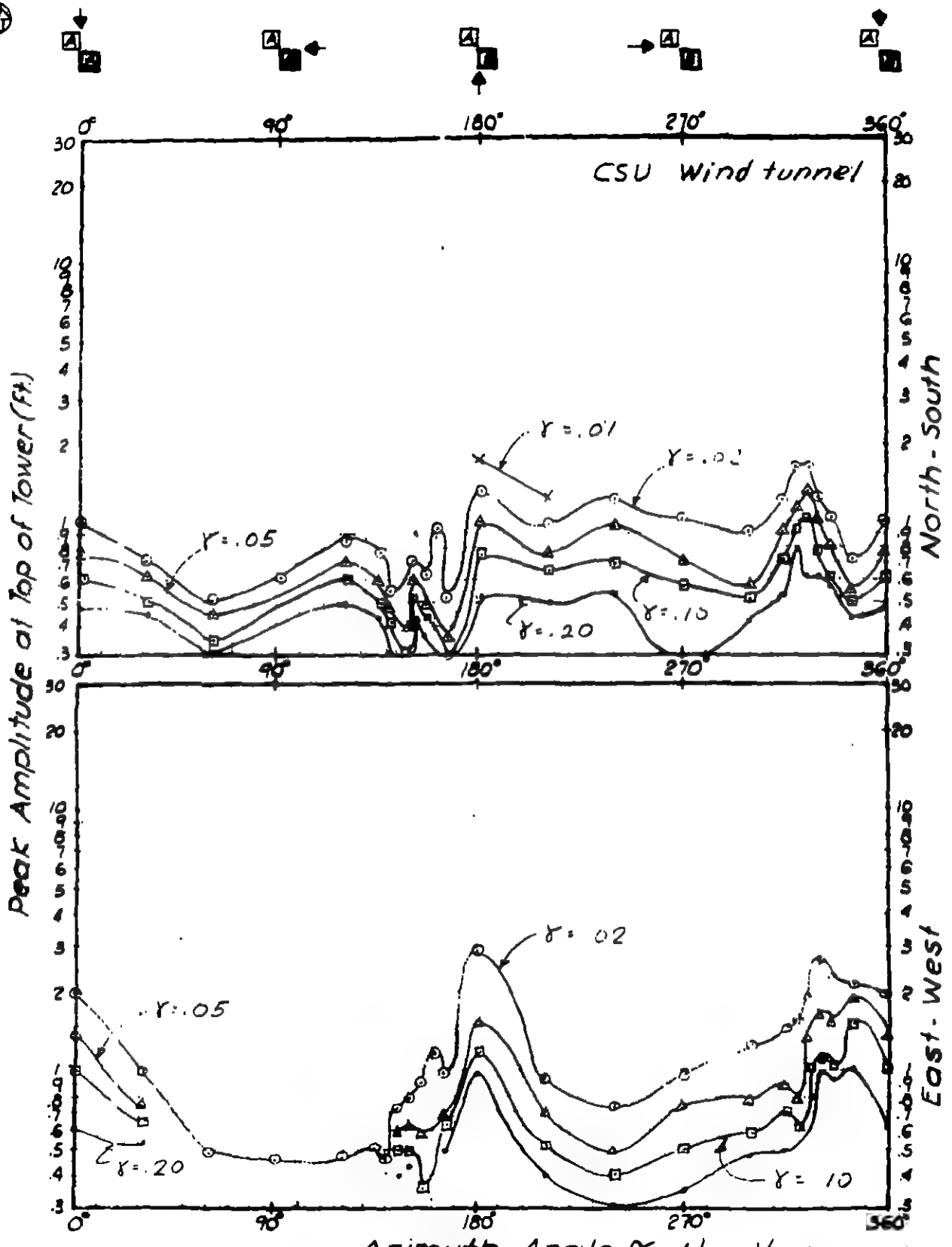

V = [illegible] m.p.h.

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 14b

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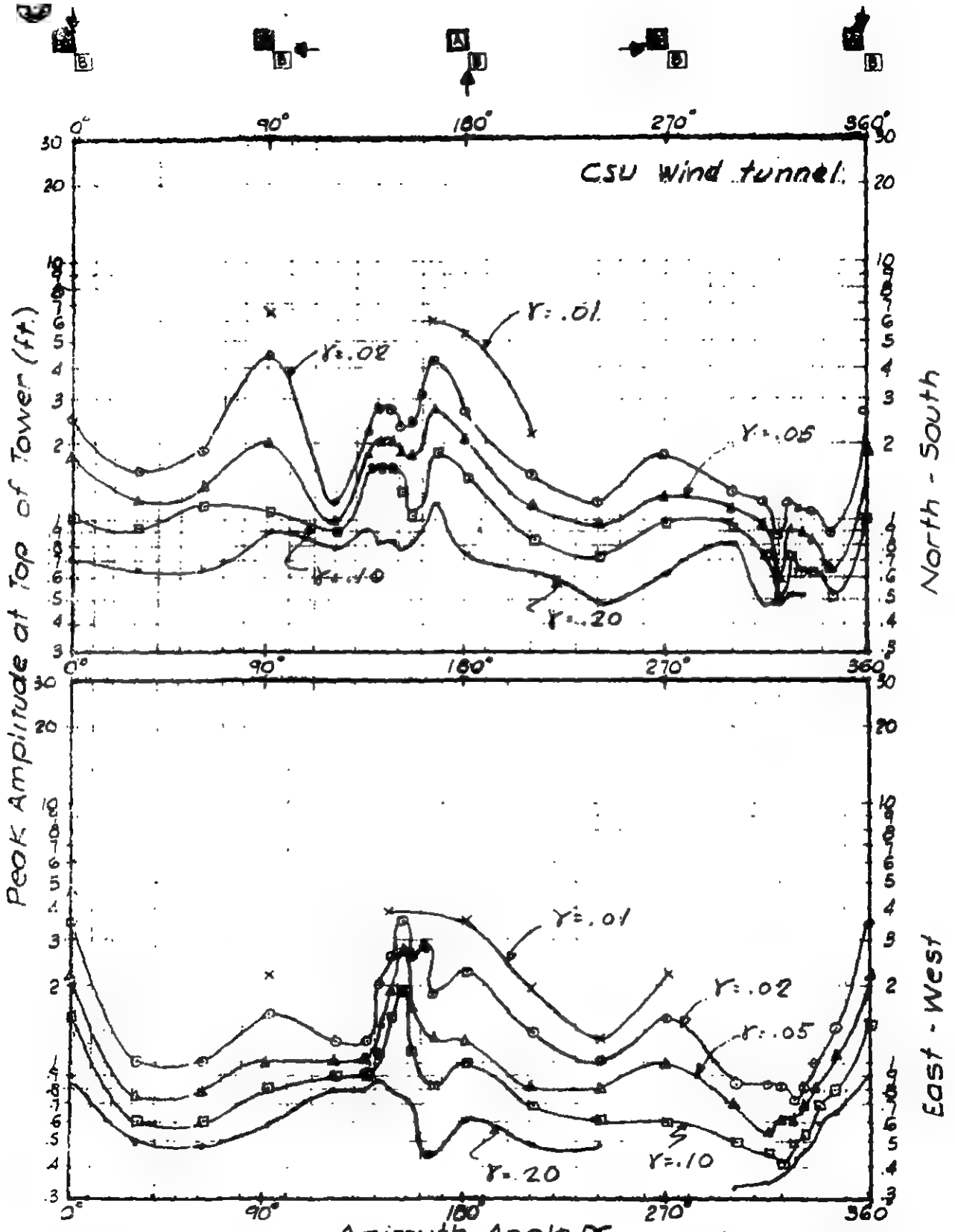

V = 150 m.p.h

New York - SW
Low frequency

TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 15a

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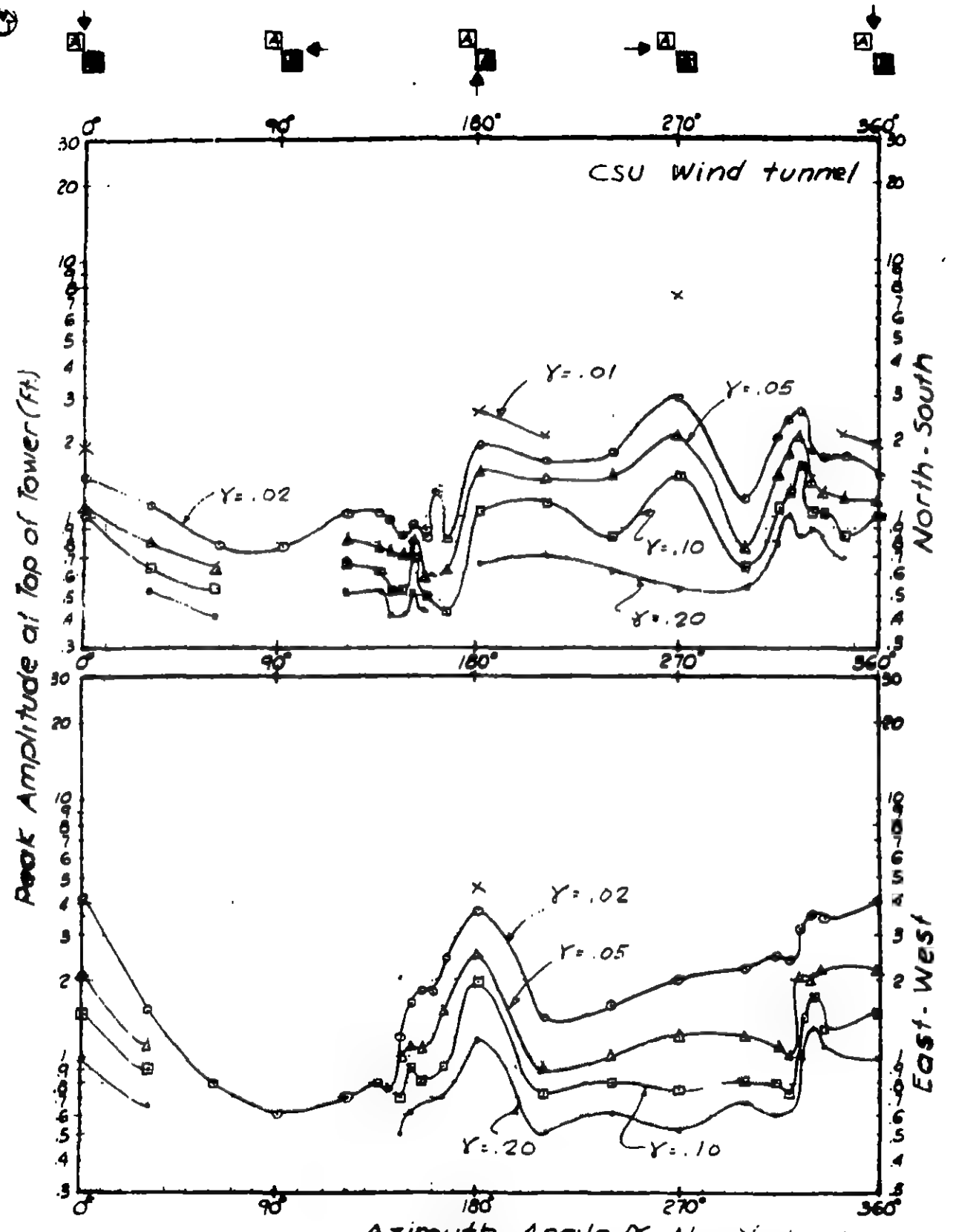

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 15b

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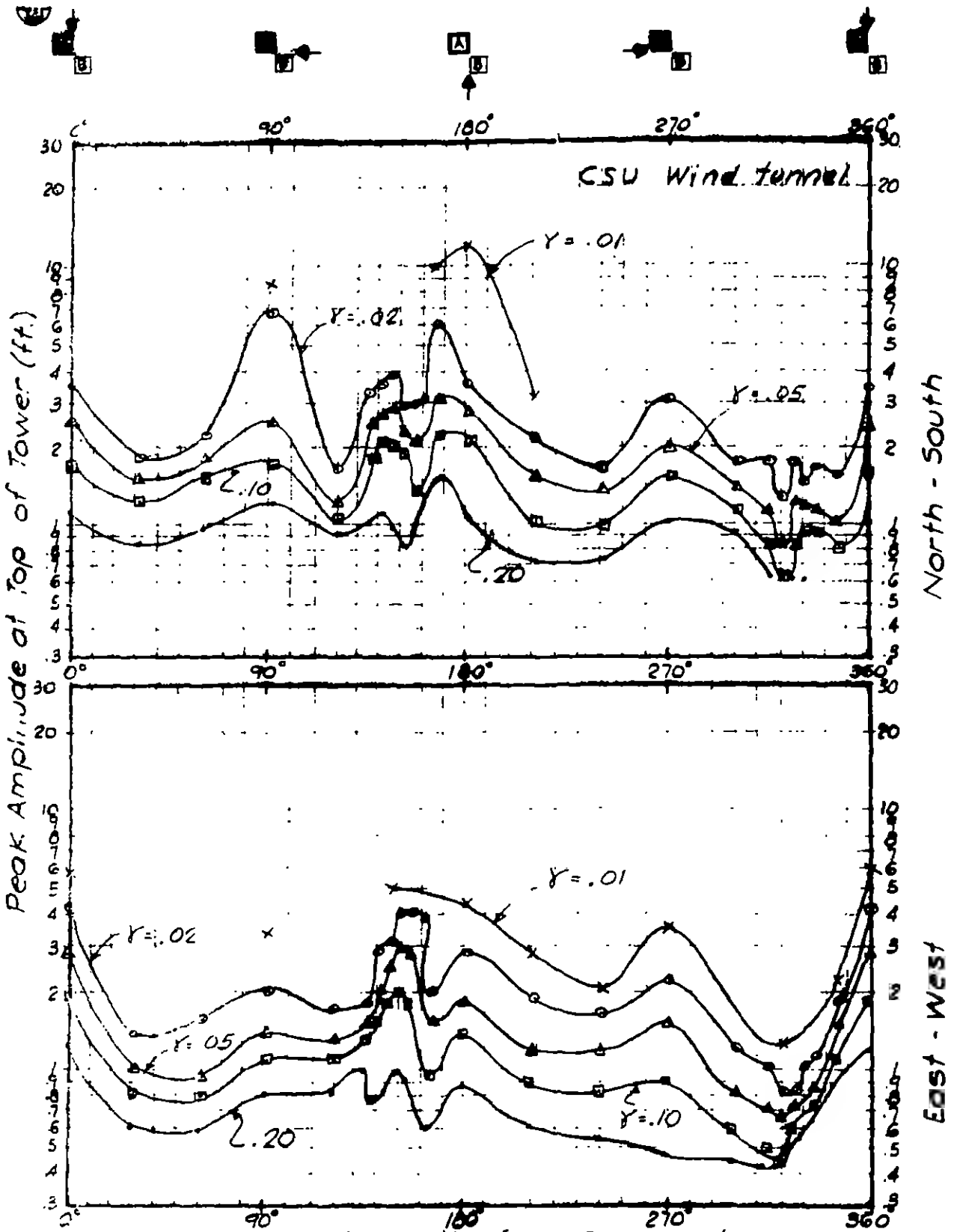

TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 16a

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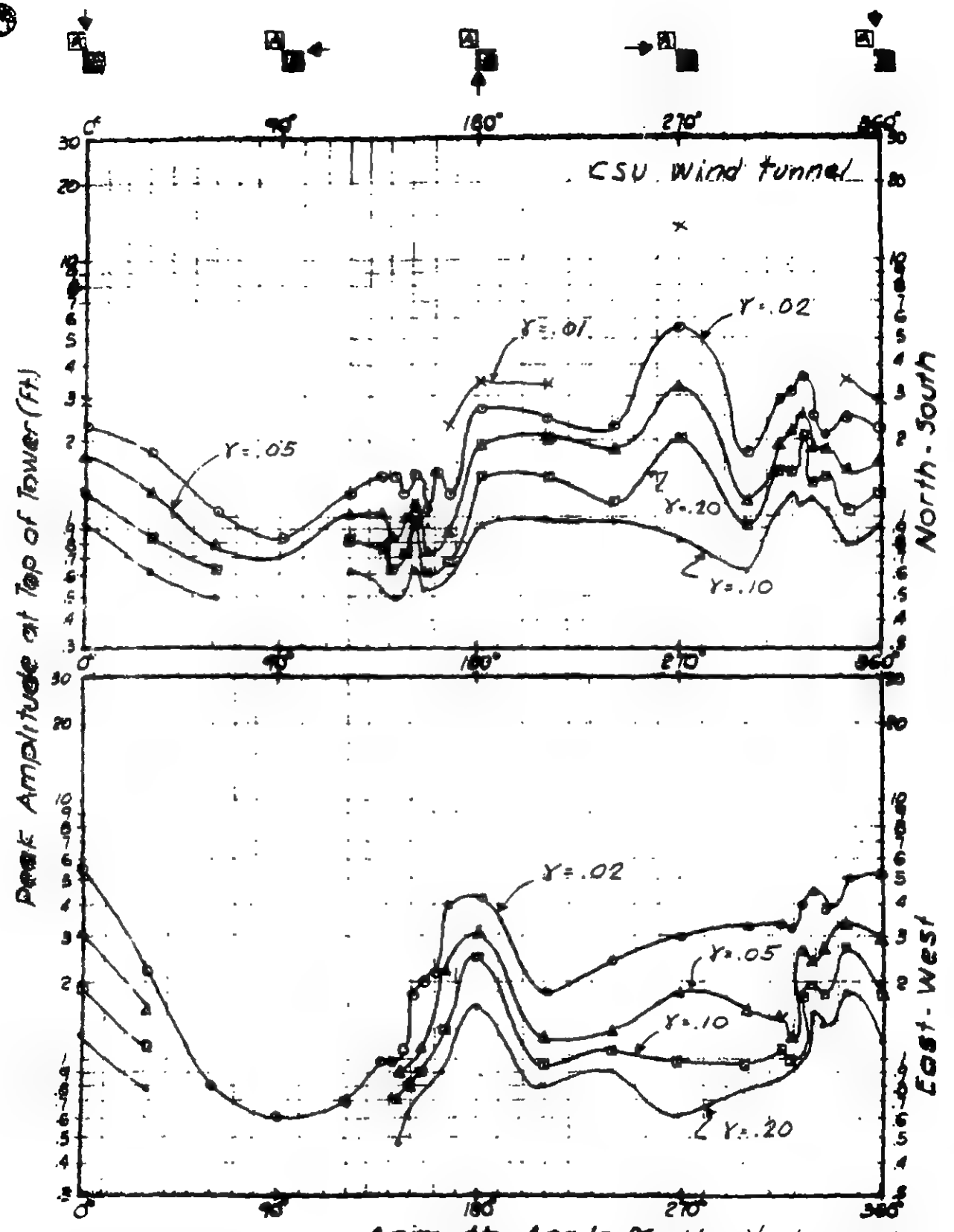

V = 175 m.p.h. Azimuth Angle α New York - SW Low frequency

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 16b

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TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

Fig. 17a

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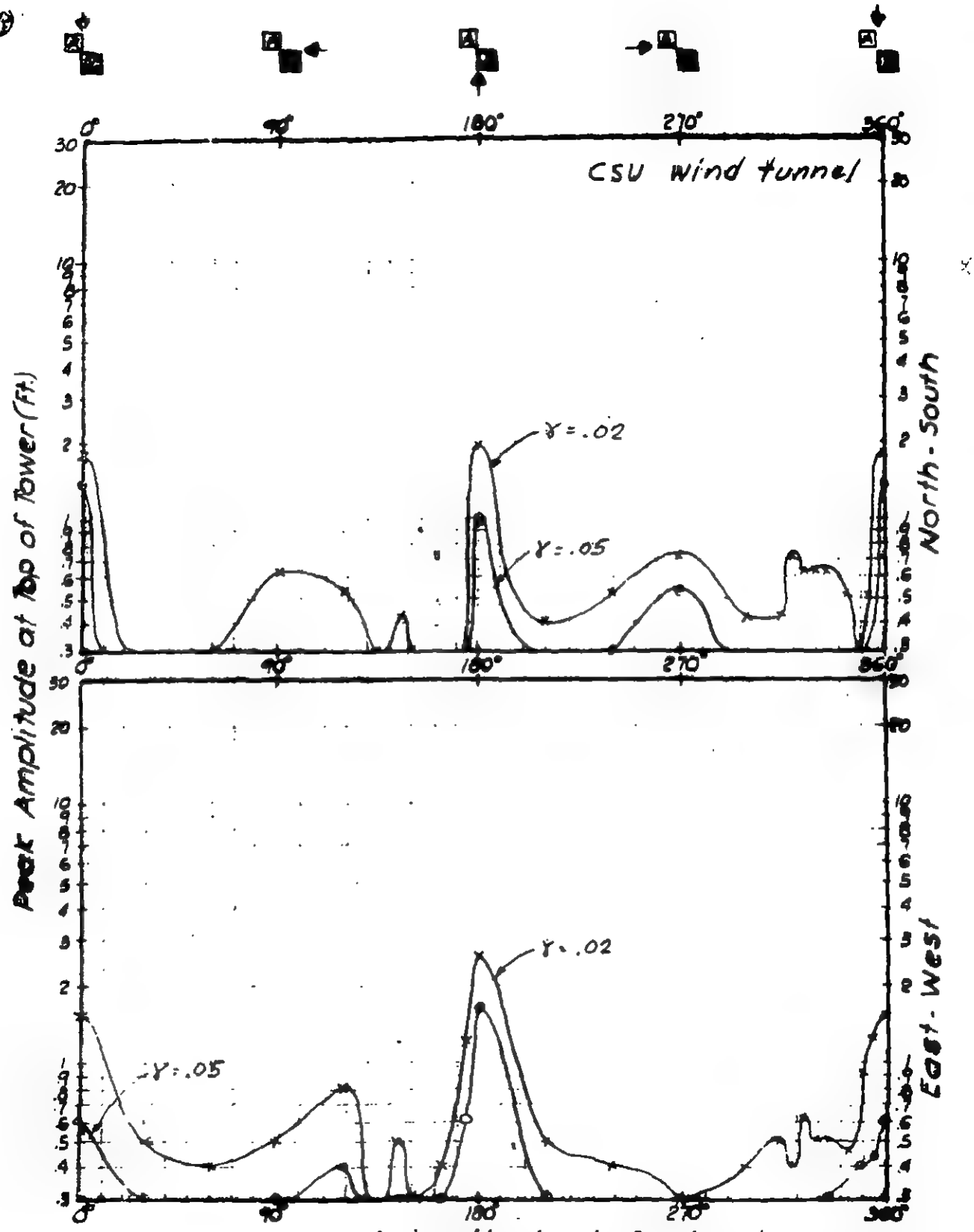

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 17b

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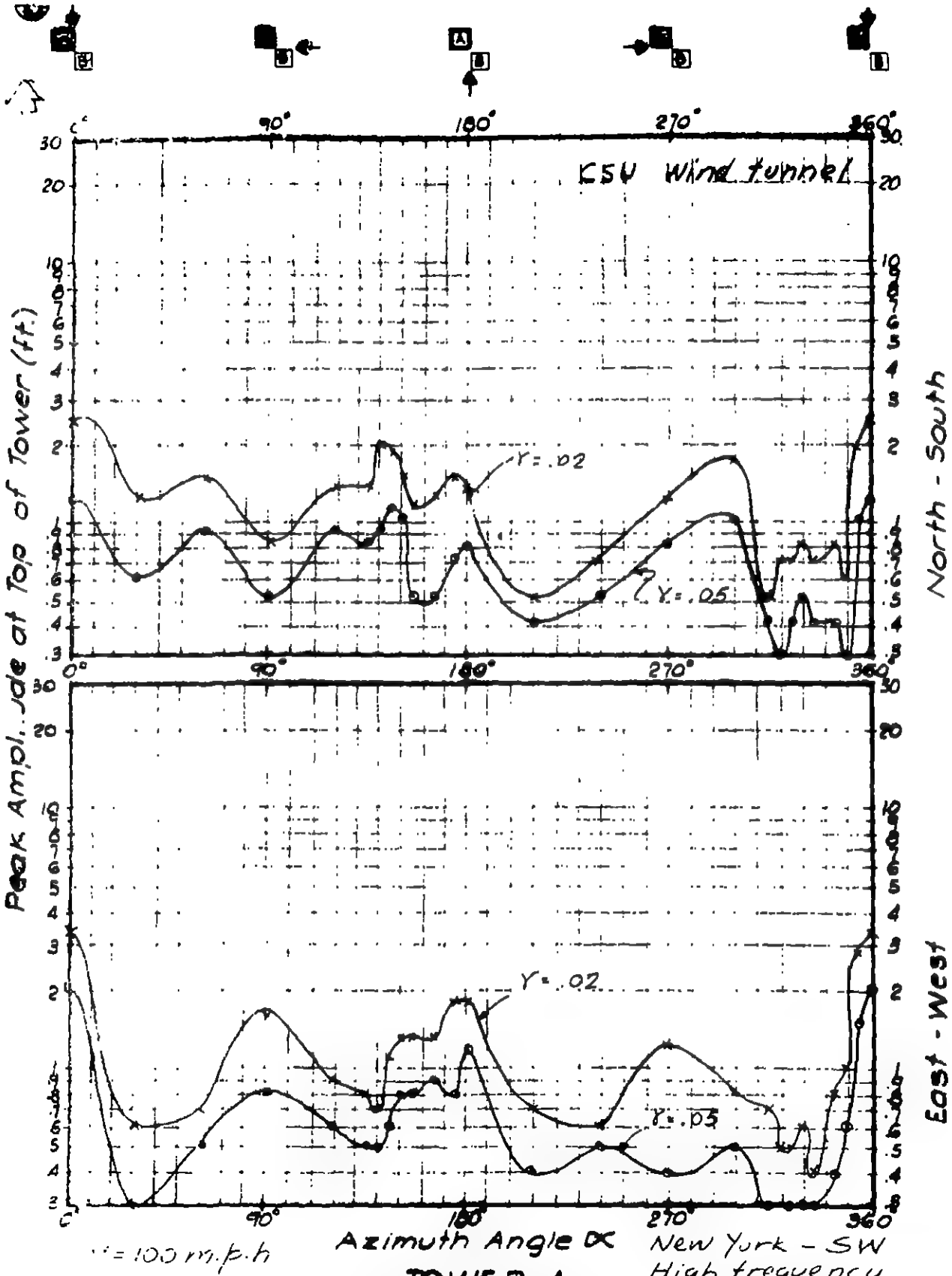

TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 18a

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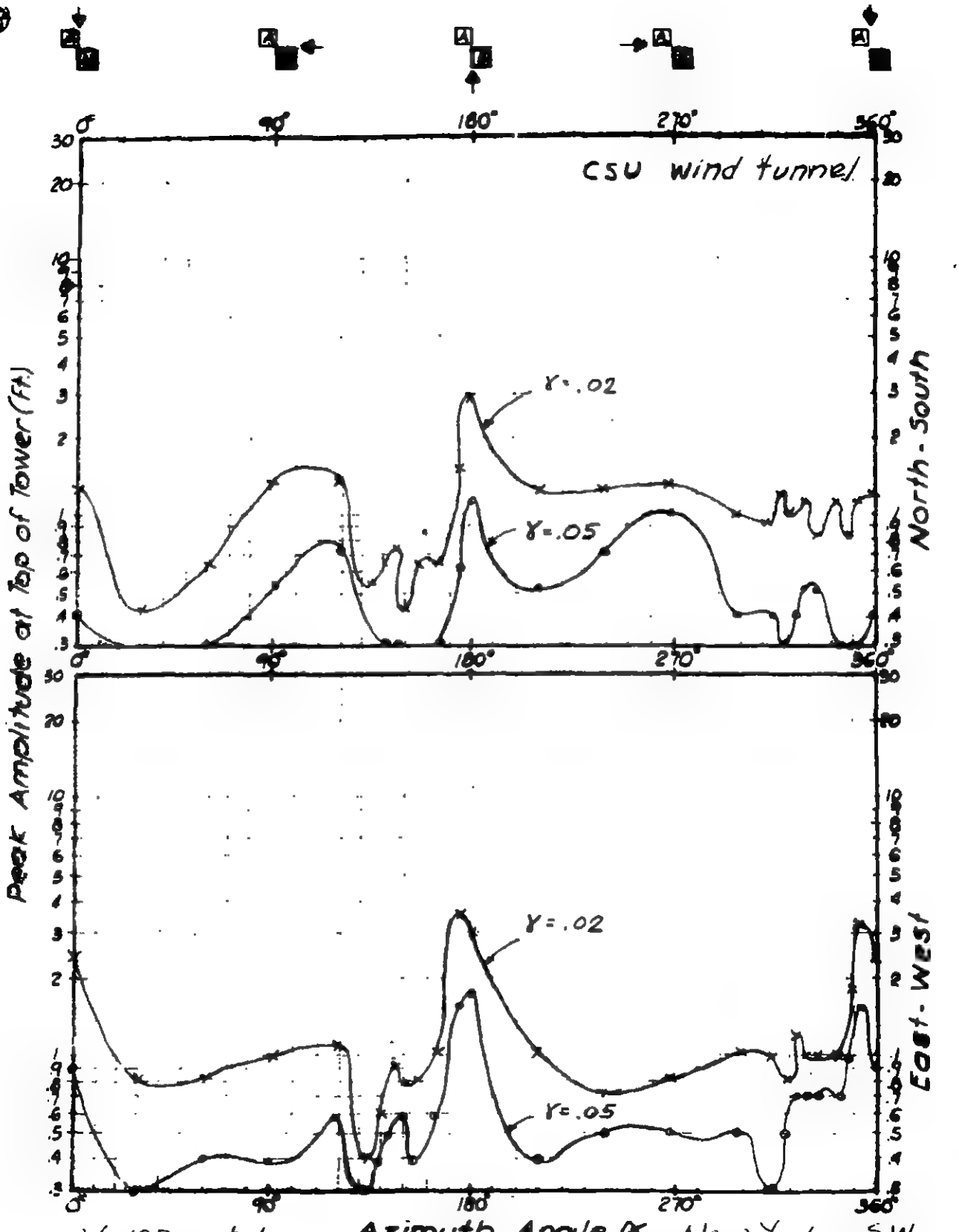

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 18b

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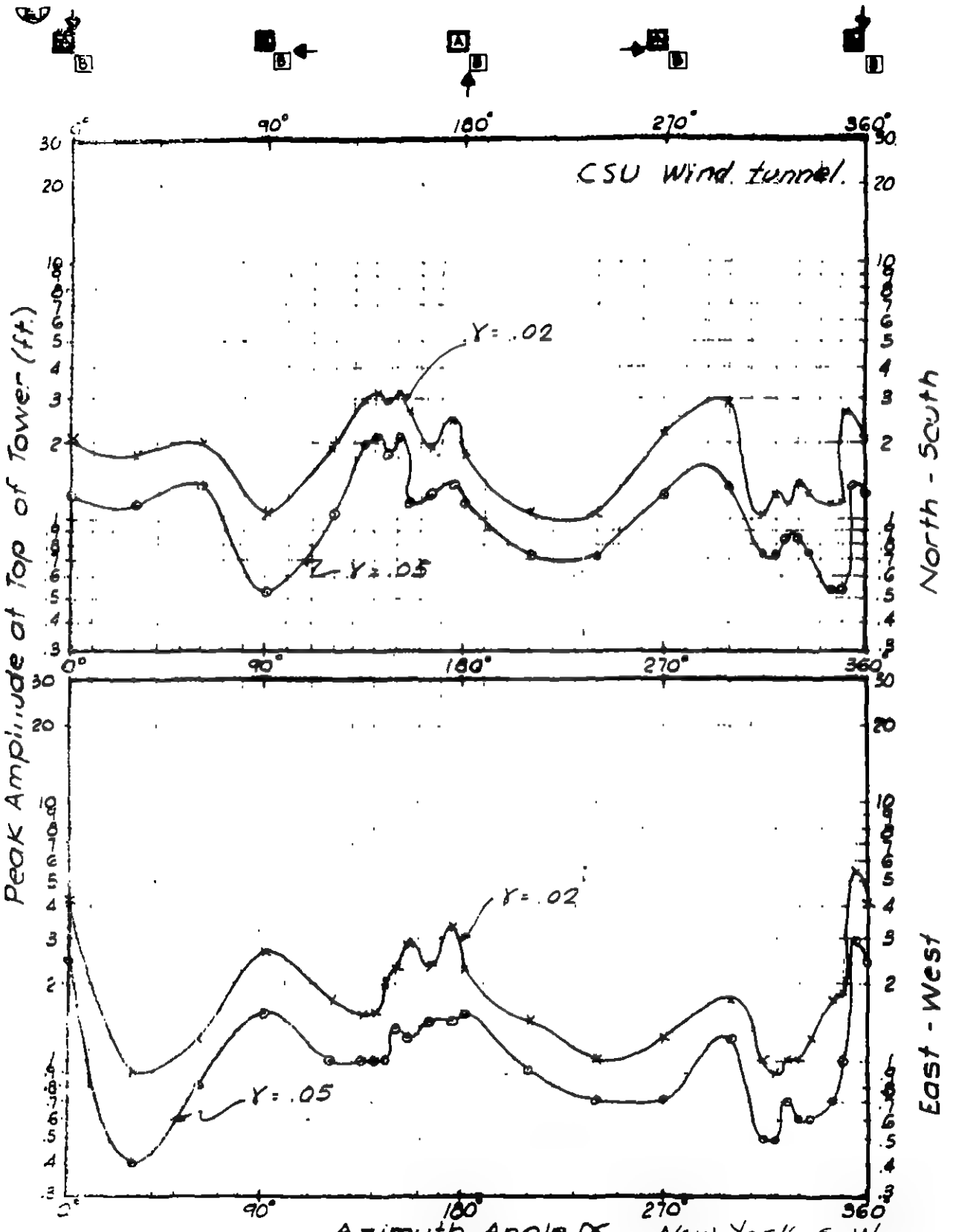

TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 19a

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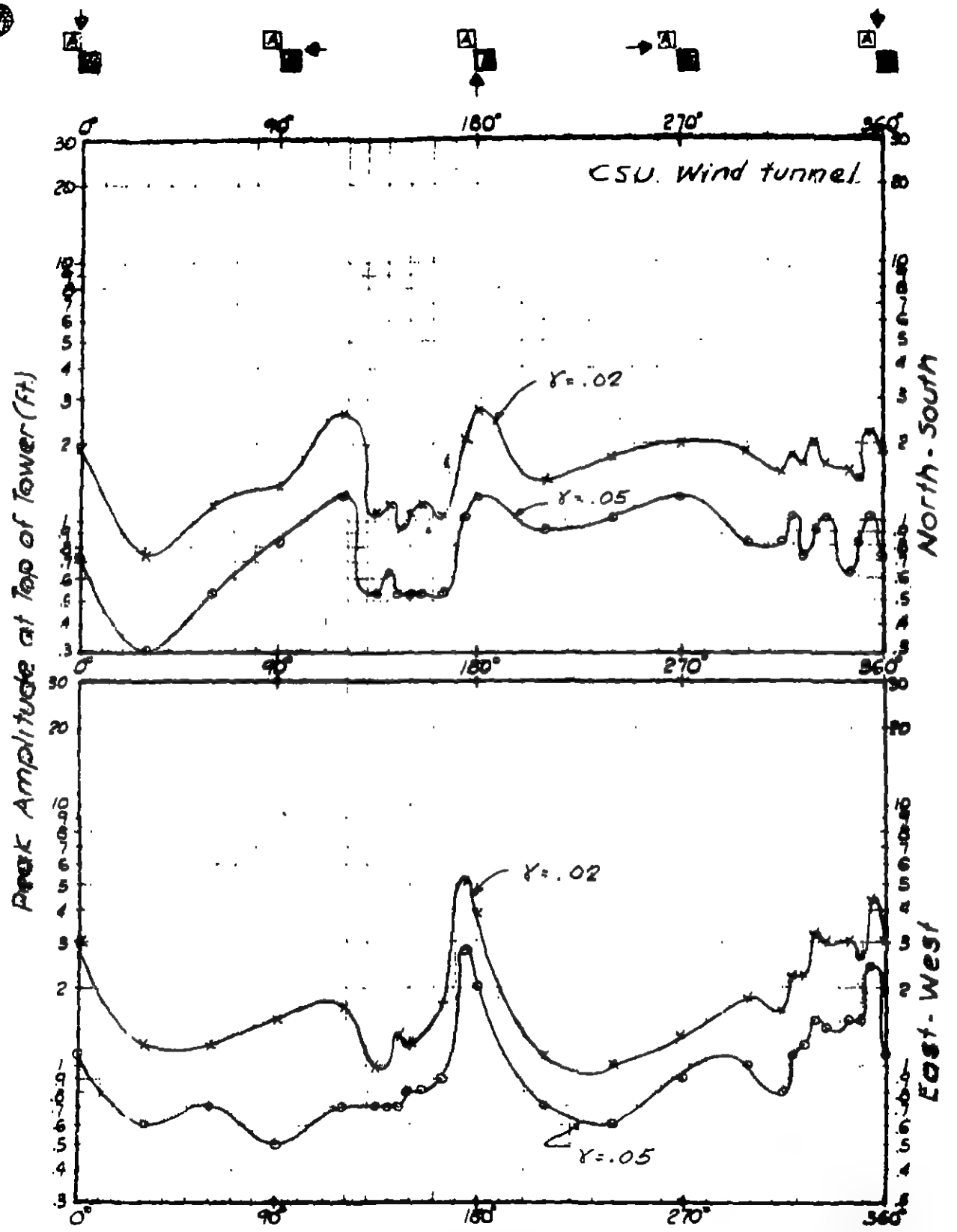
EXP 006953



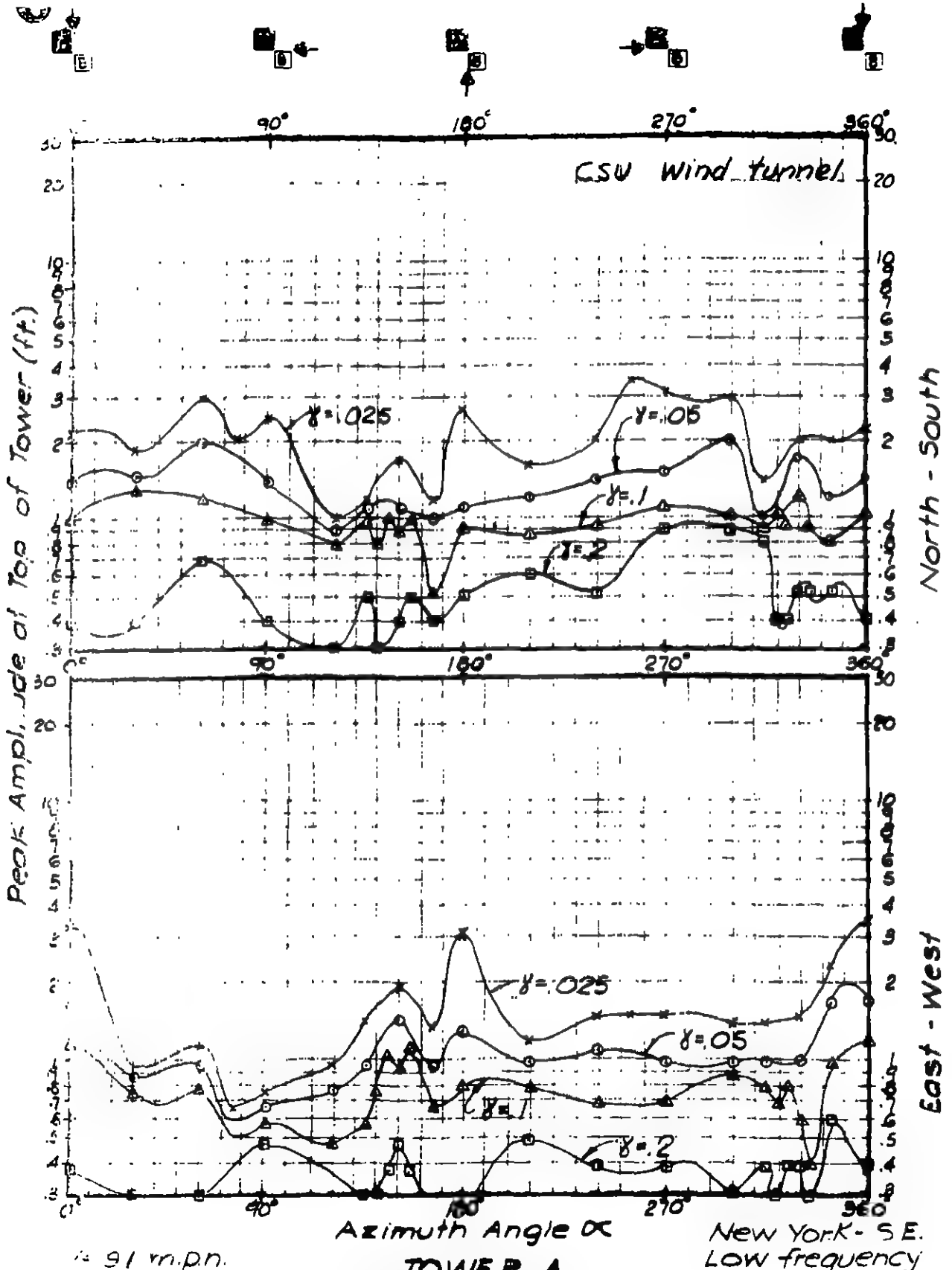
V = 125 m.p.h

Azimuth Angle ∝ New York S-W High frequency

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 19b



TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 209

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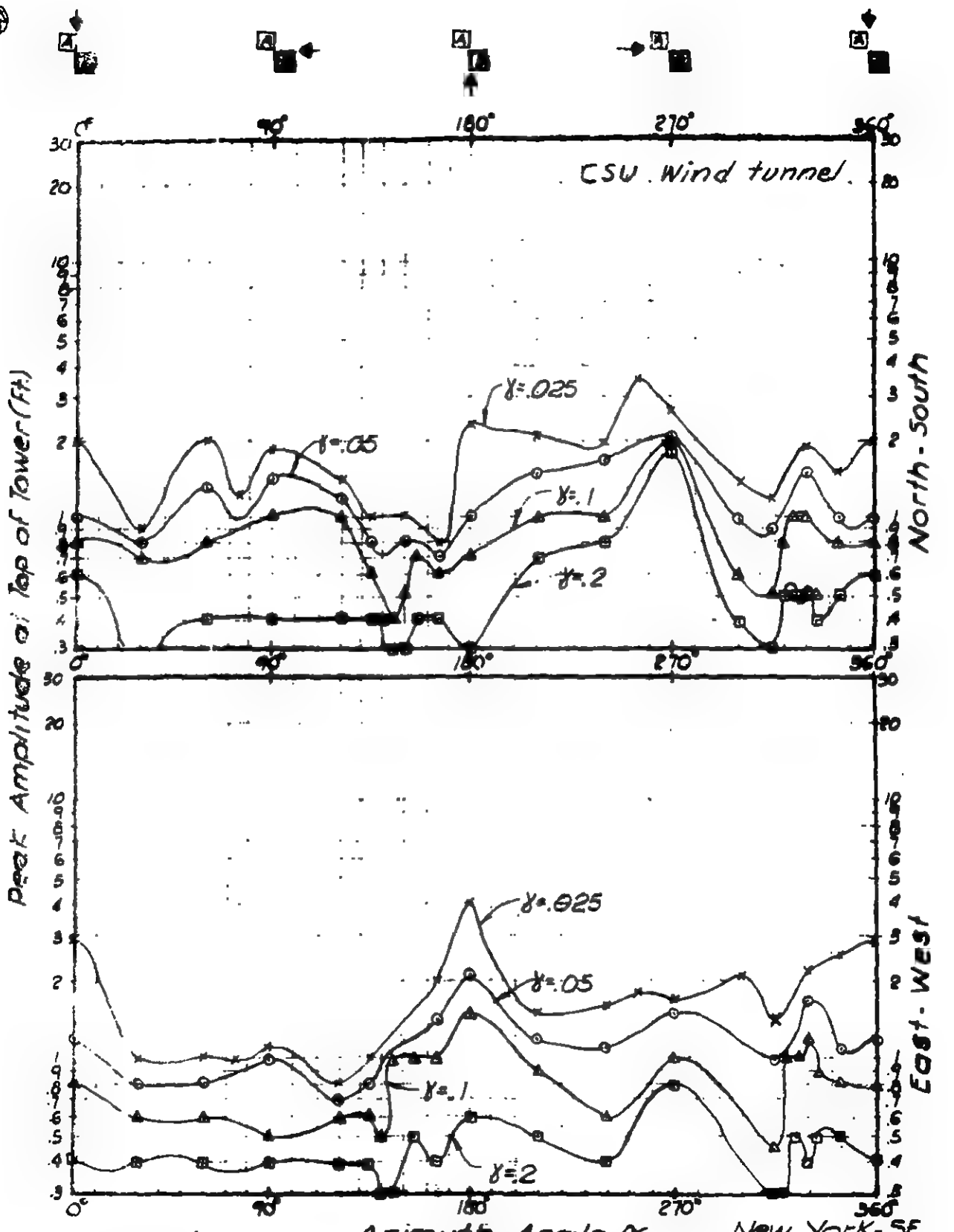
EXP 006955



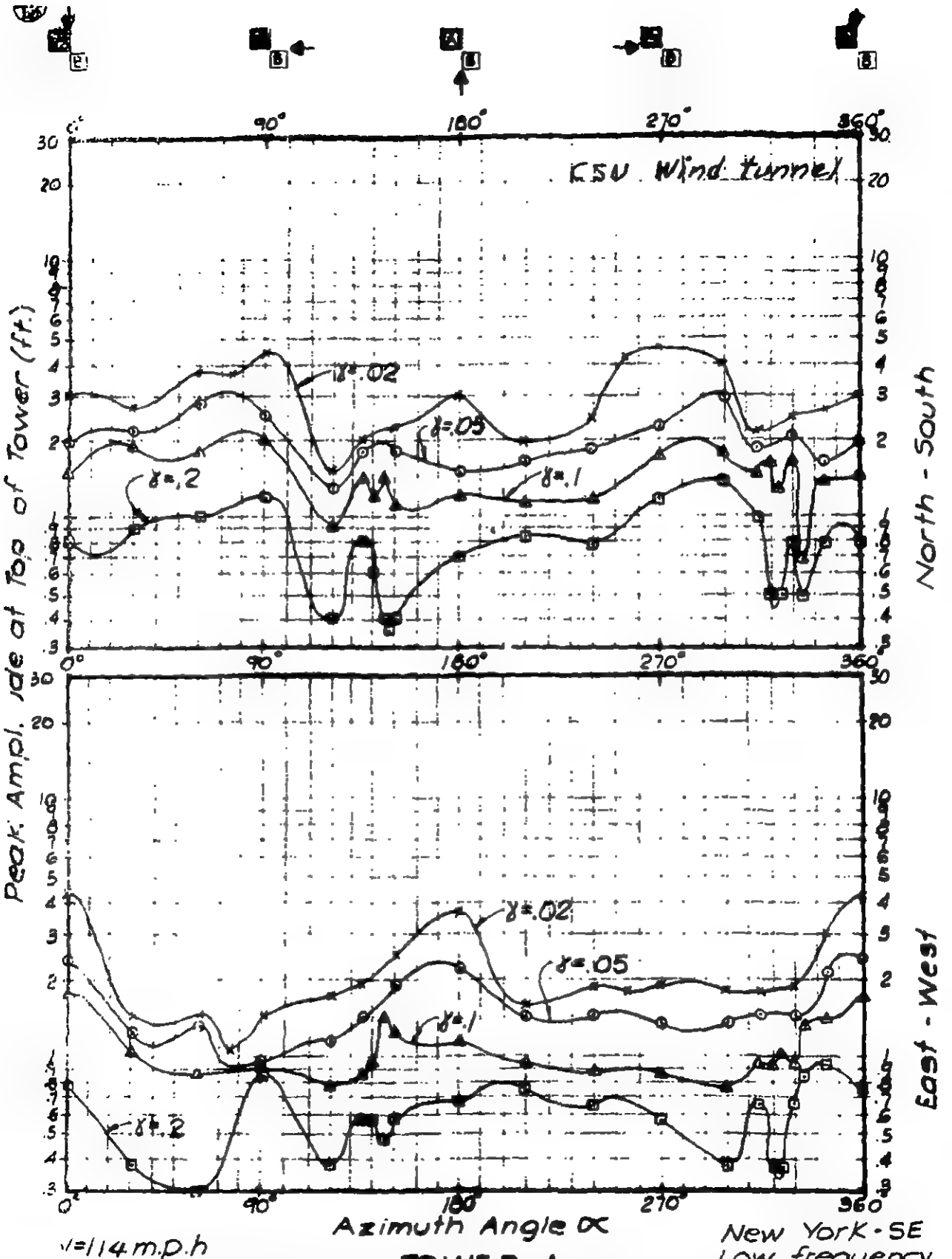
TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 206

CONFIDENTIAL

EXP 006956



TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 21a

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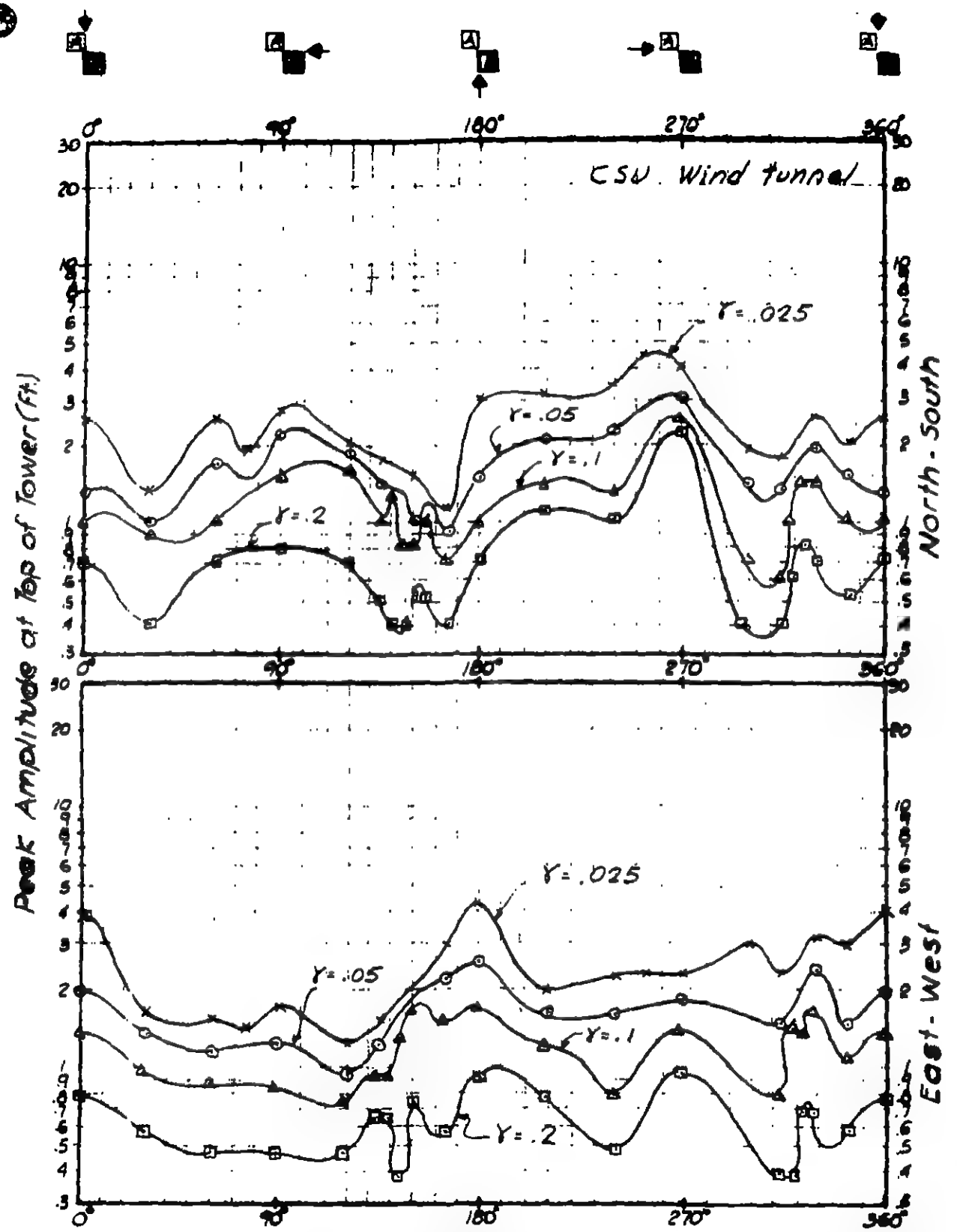
EXP 006957



V = 114 m.p.h. Azimuth Angle α New York - SE Low frequency

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 21b

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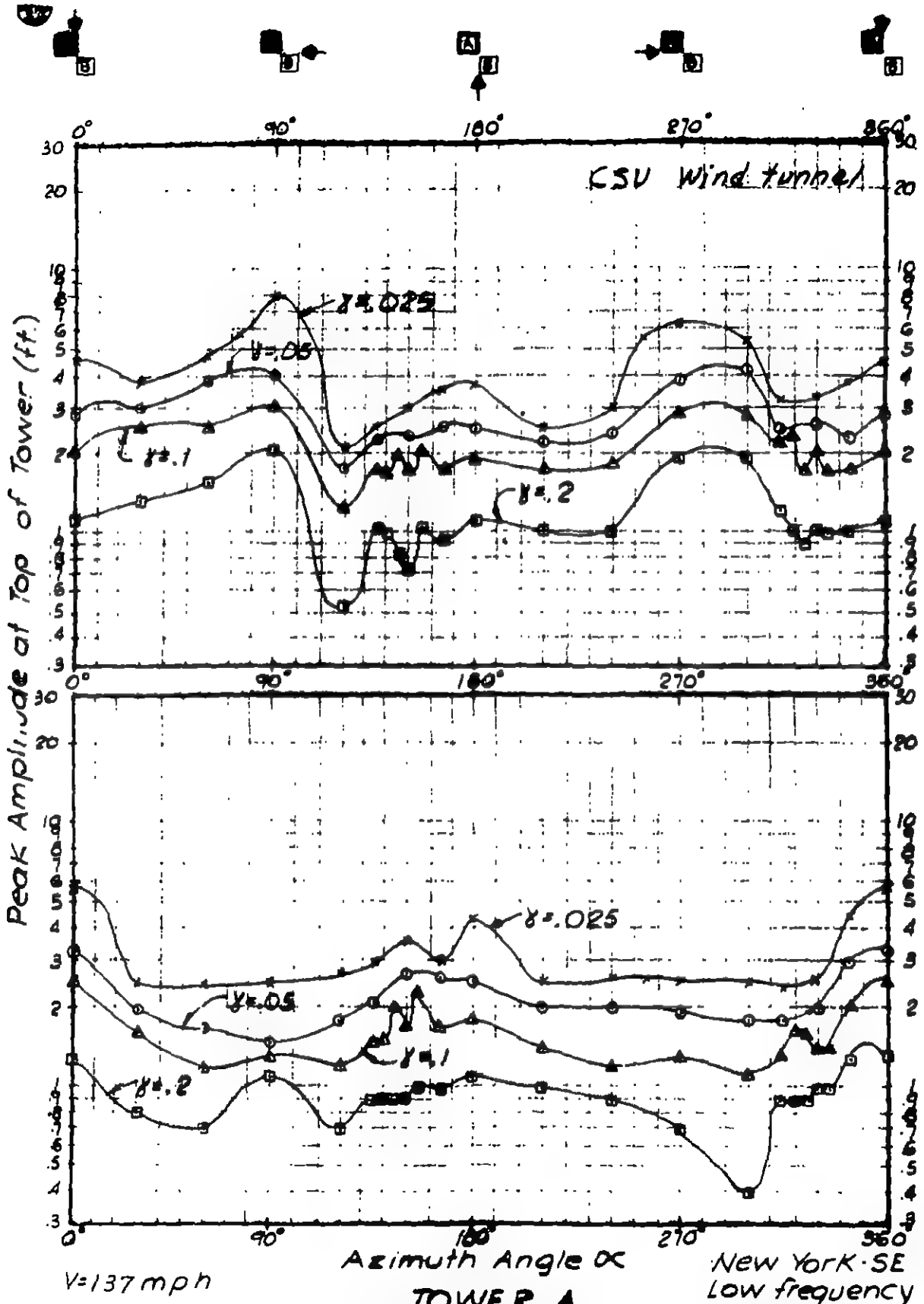
EXP 006958



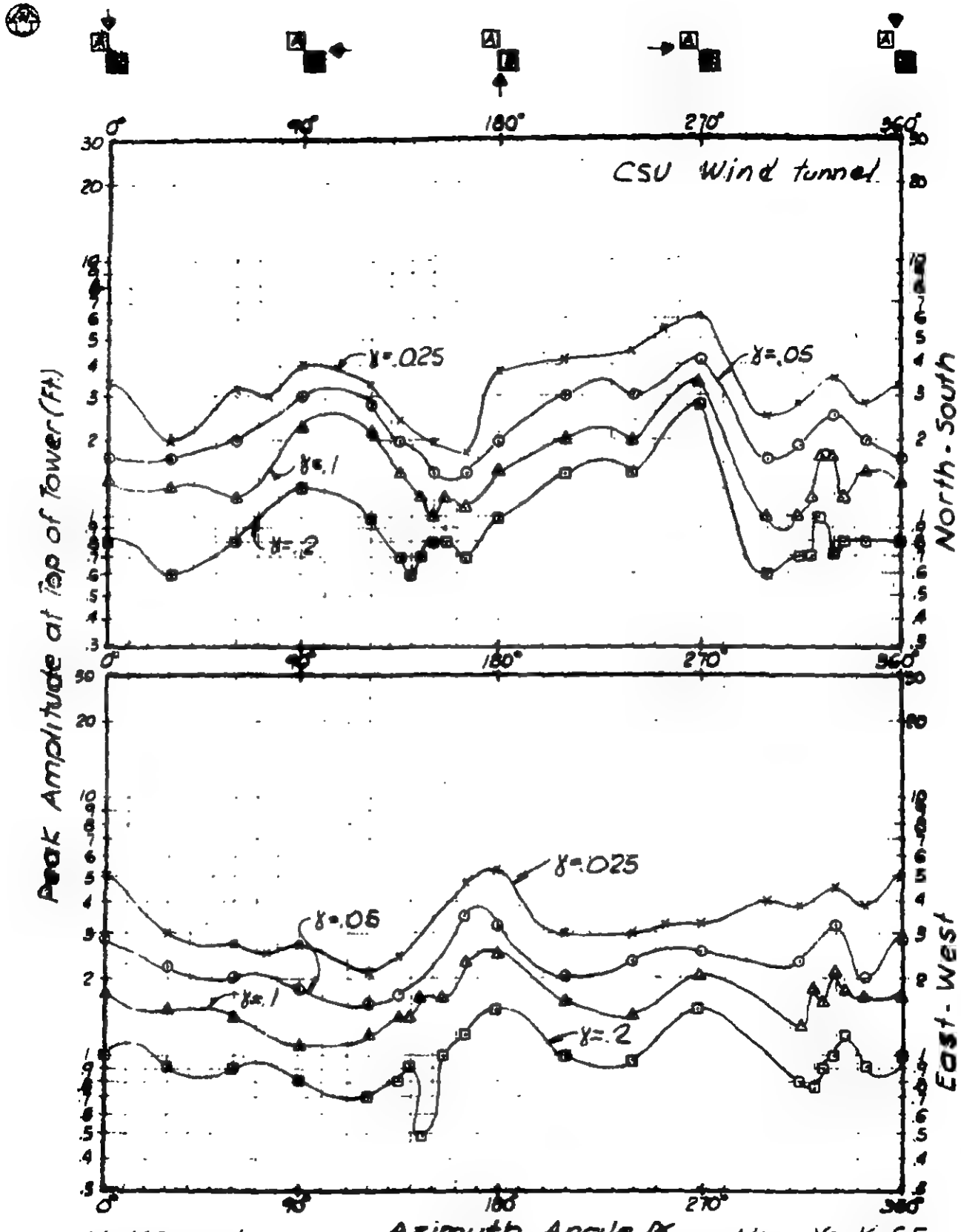
TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 22a

CONFIDENTIAL

EXP 006959



TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 225

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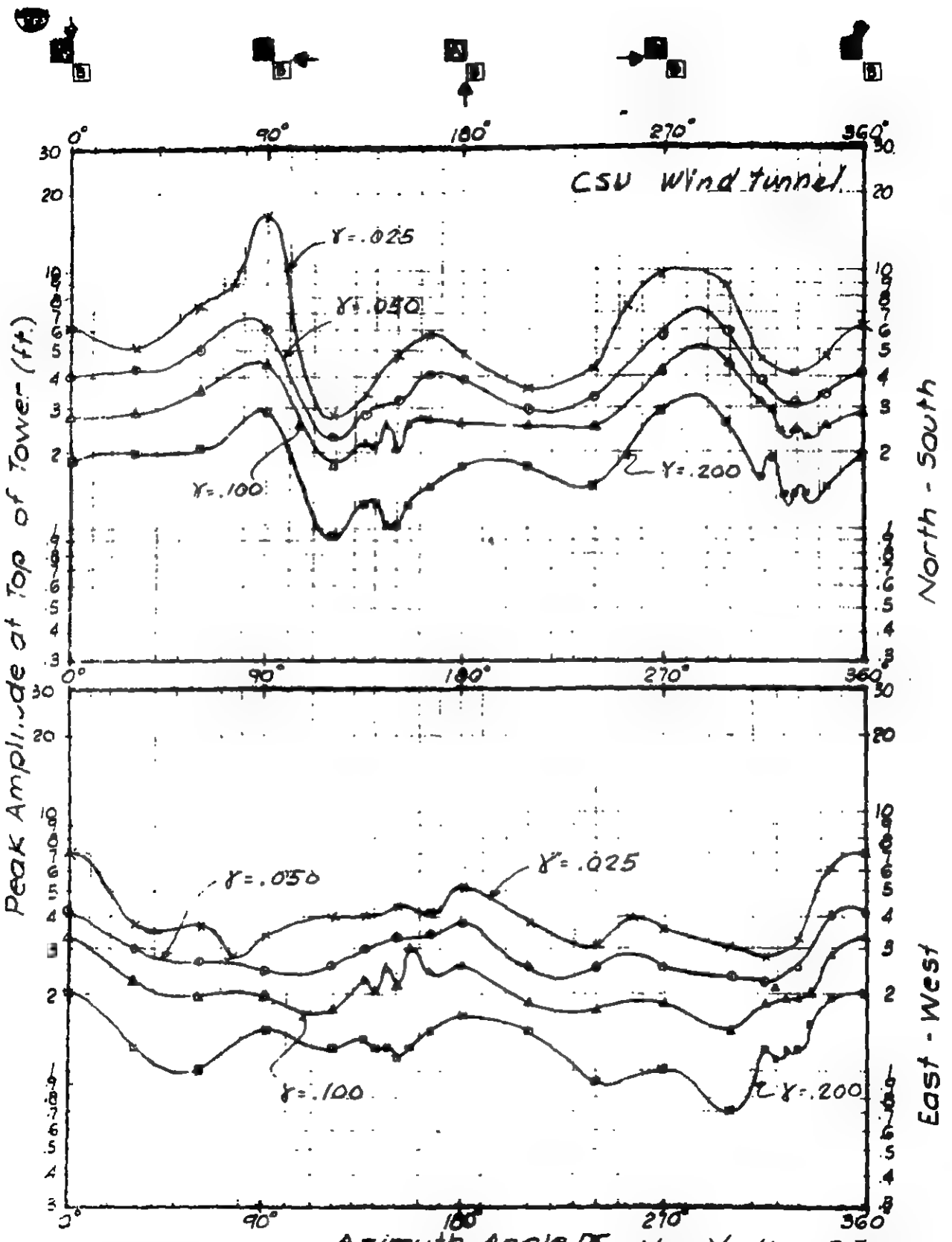
EXP 006960



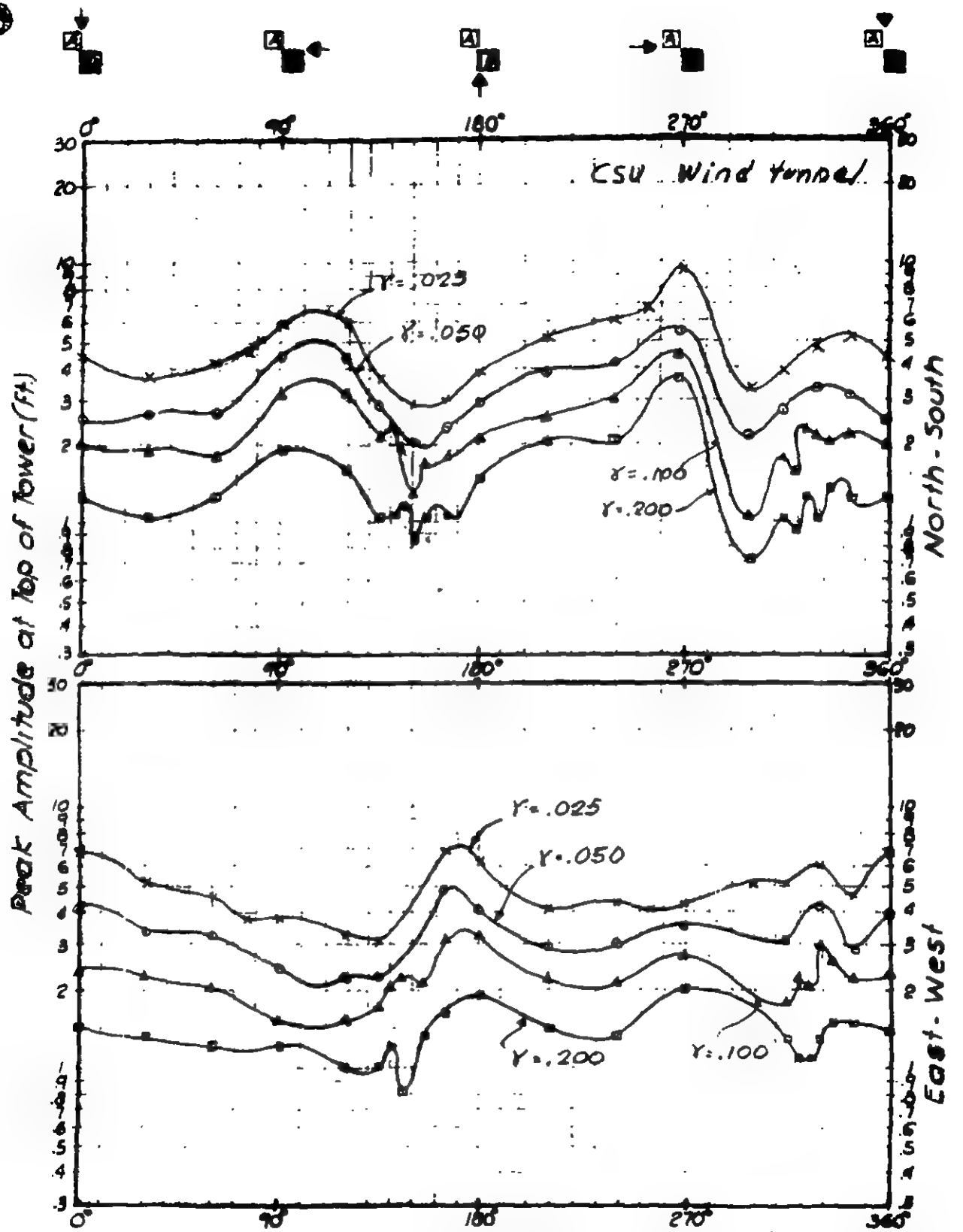
TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 23a

CONFIDENTIAL

EXP 006961



V = 160 m.p.h

Azimuth Angle ∝ New York - SE

Low frequency

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 23b

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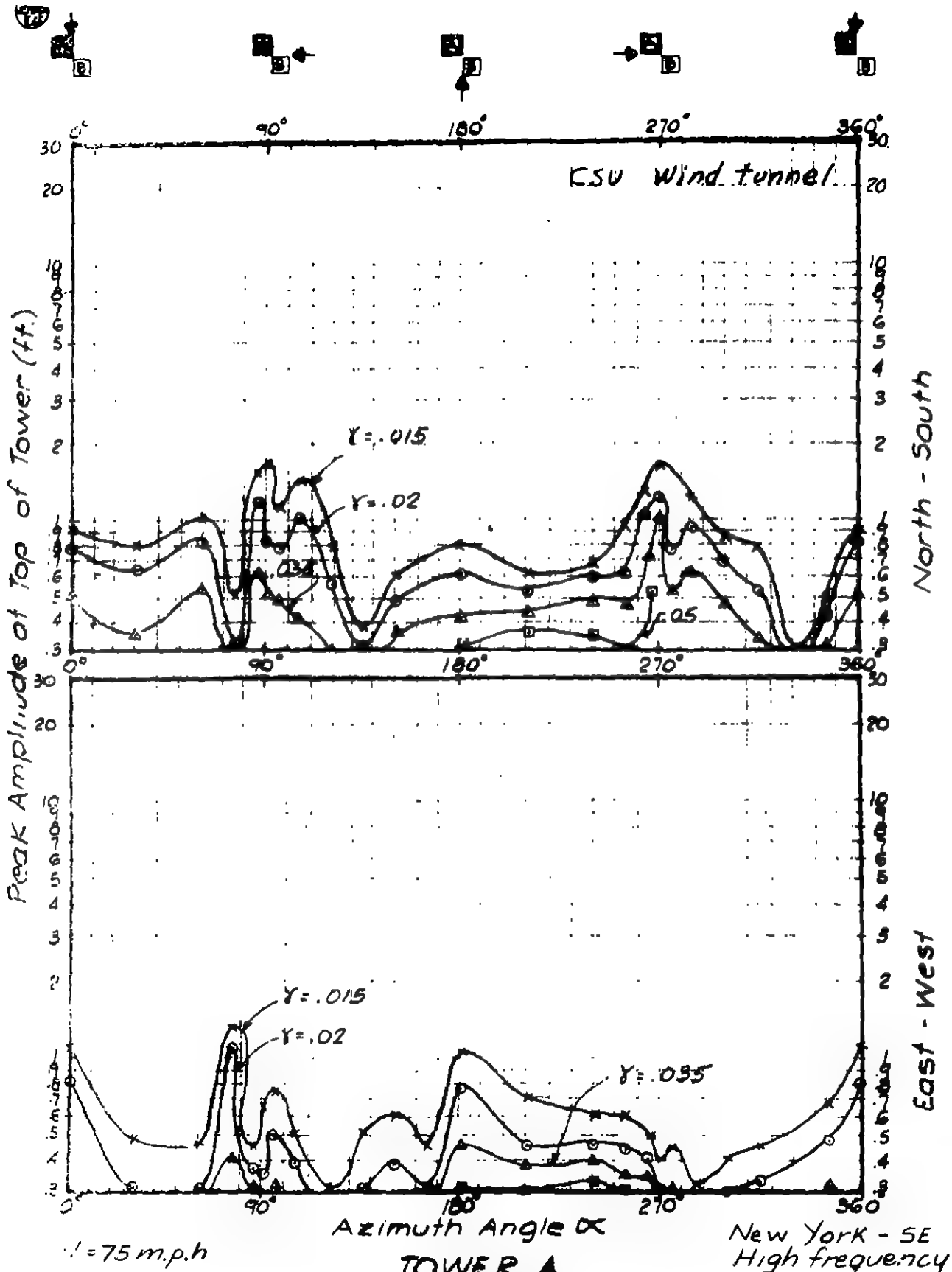
EXP 006962

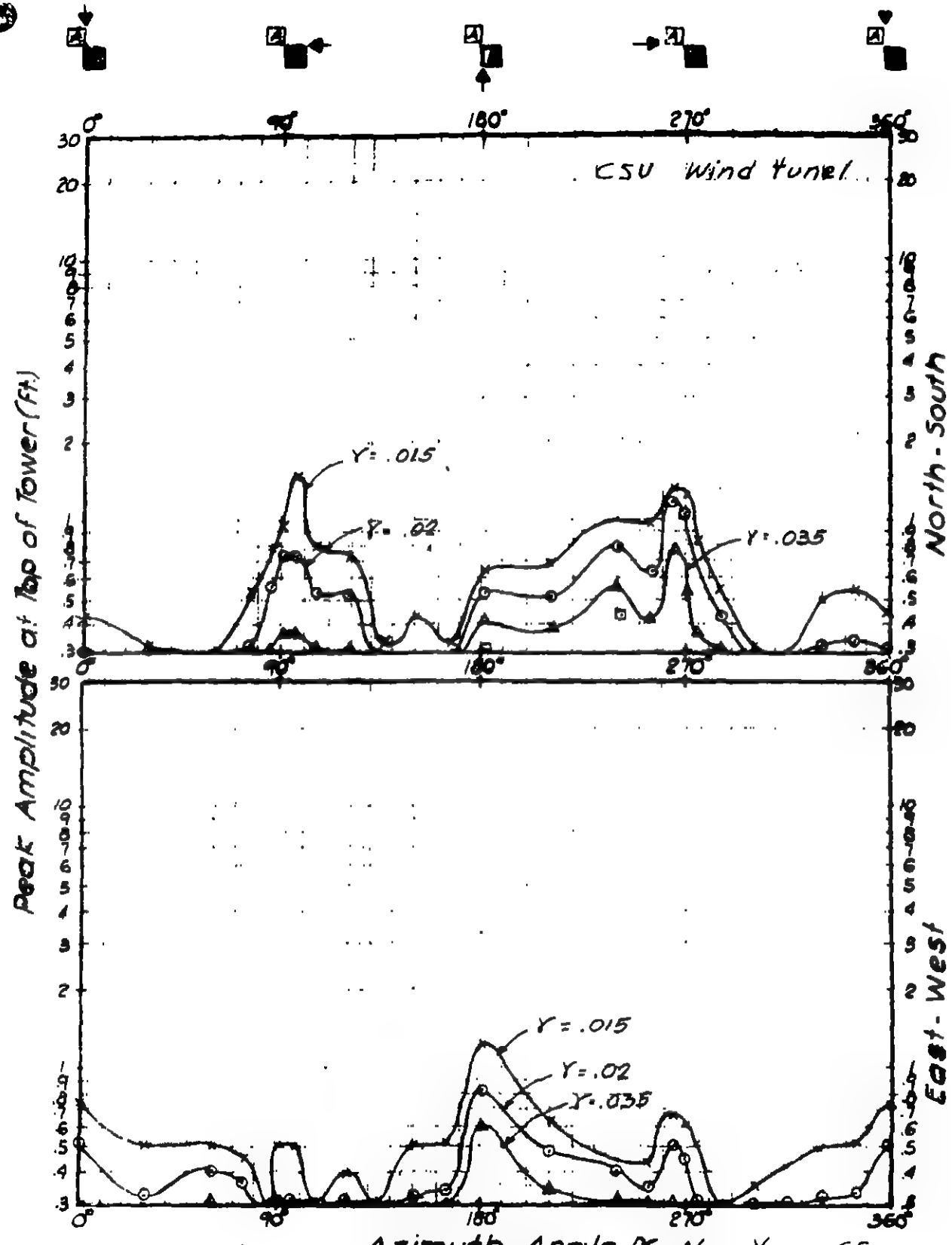


TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 249

EXP 006963



TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 24b

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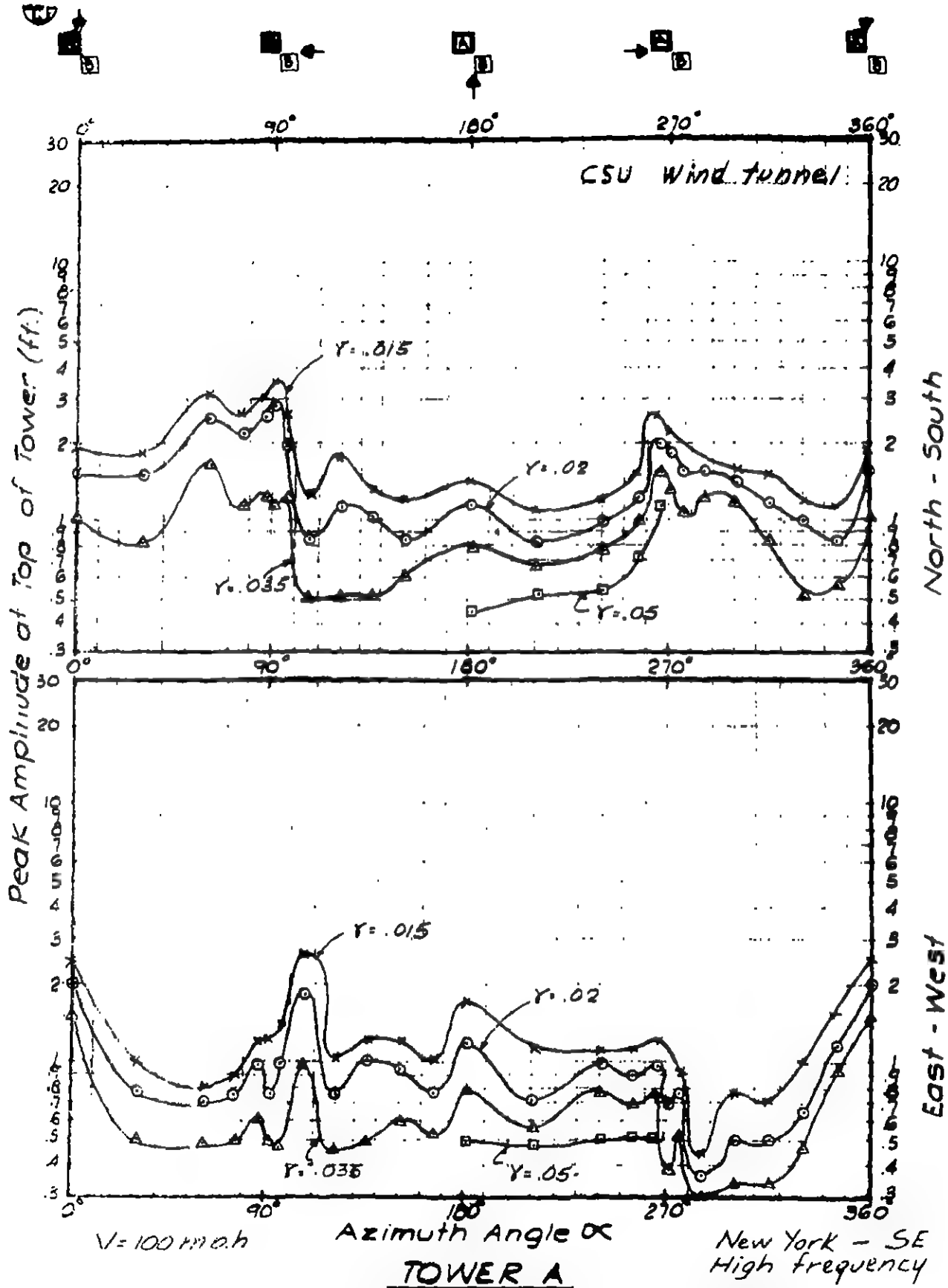
EXP 006964



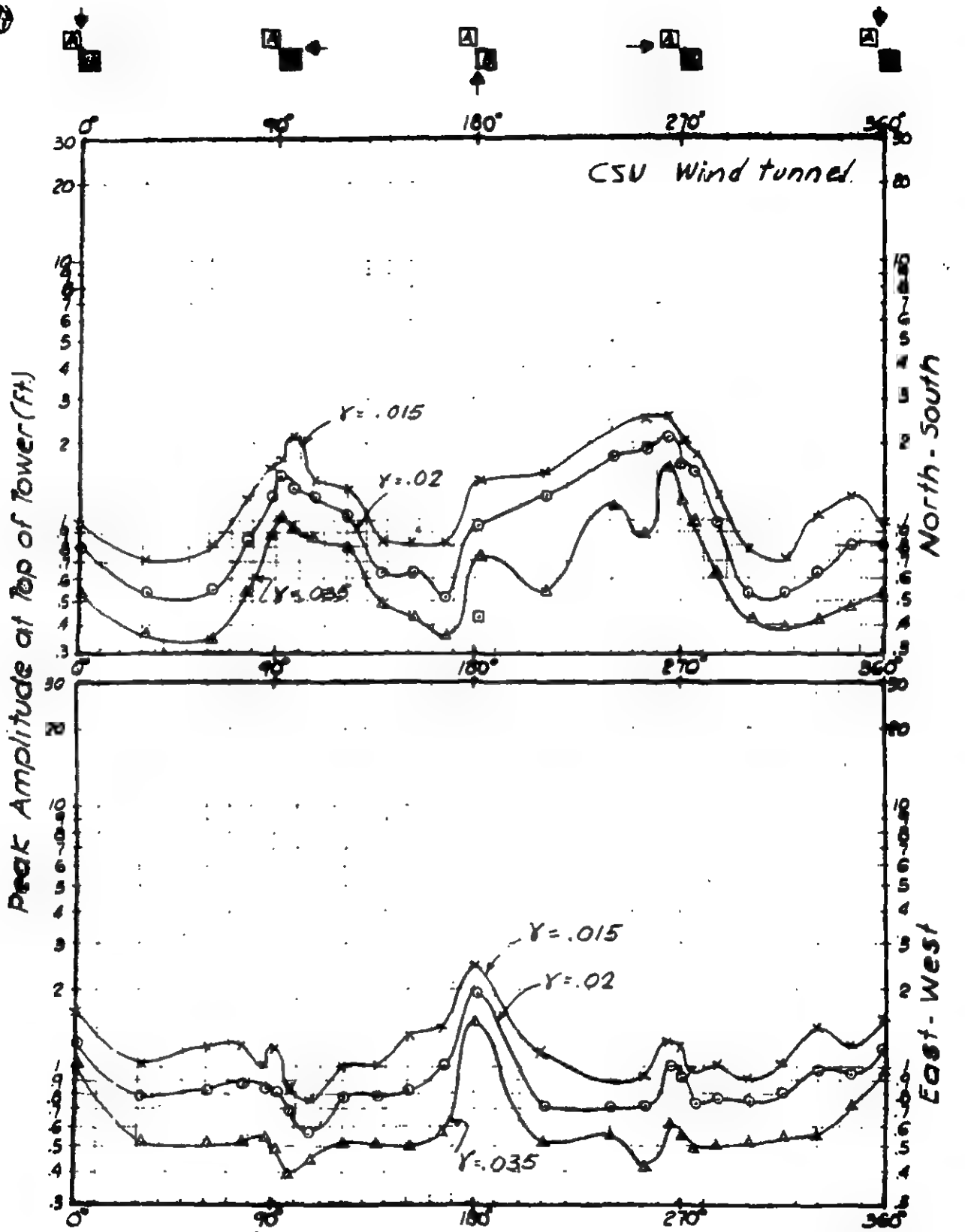
TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 25a

CONFIDENTIAL

EXP 006965



TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 26b

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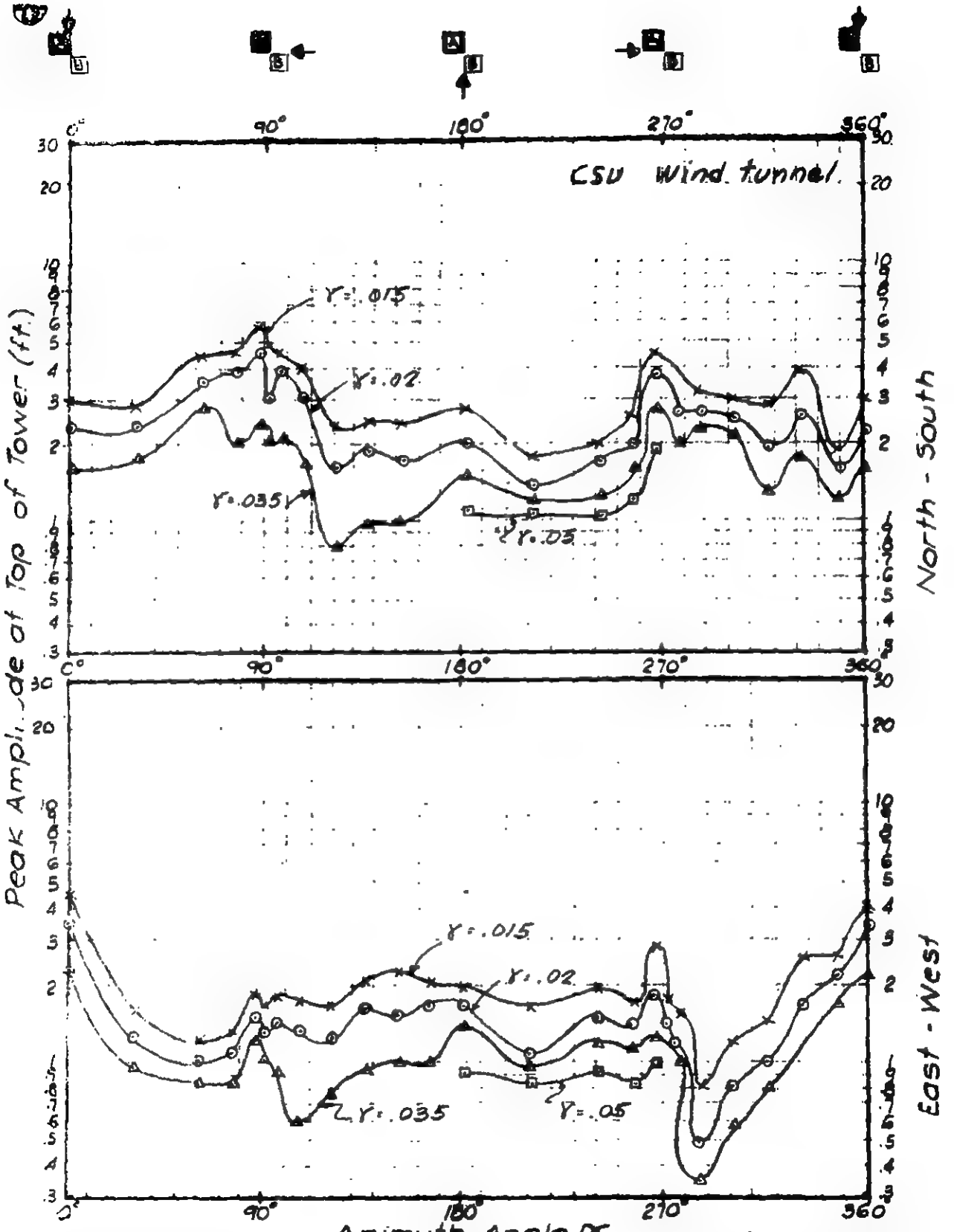
EXP 006966

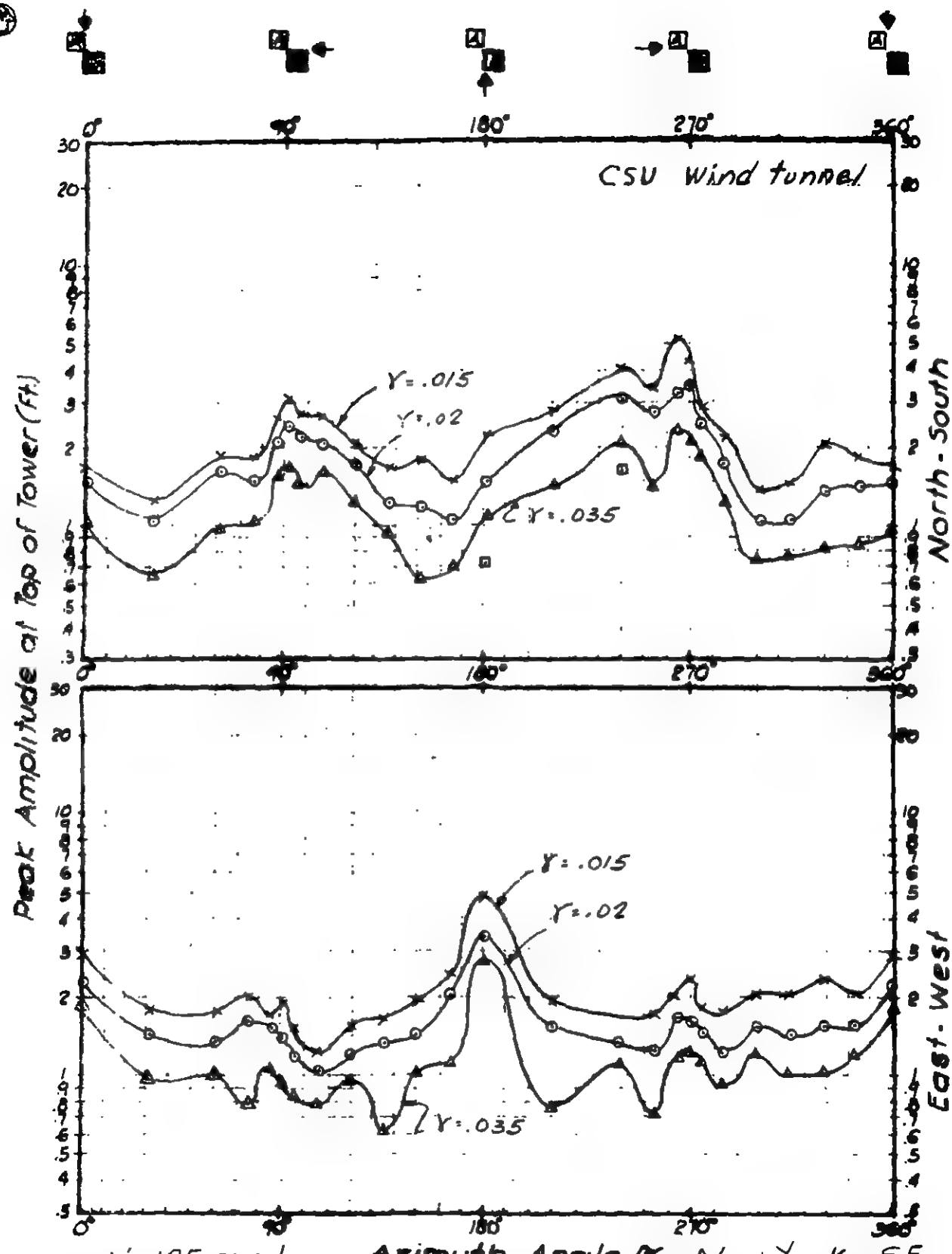


TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 26a

EXH 006967



TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 26b

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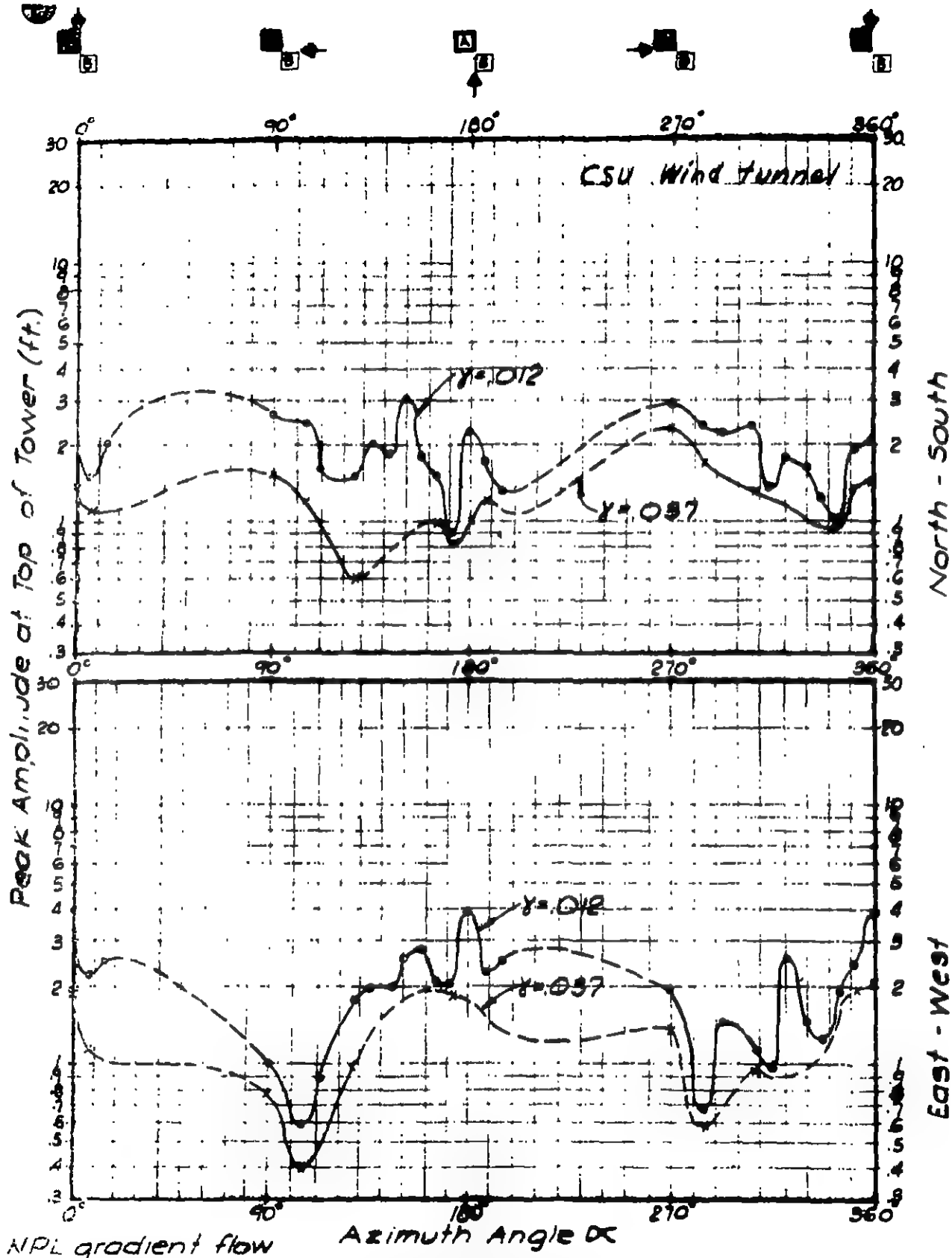
EXP 006968



NPL gradient flow
V=100 mph

TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 27a

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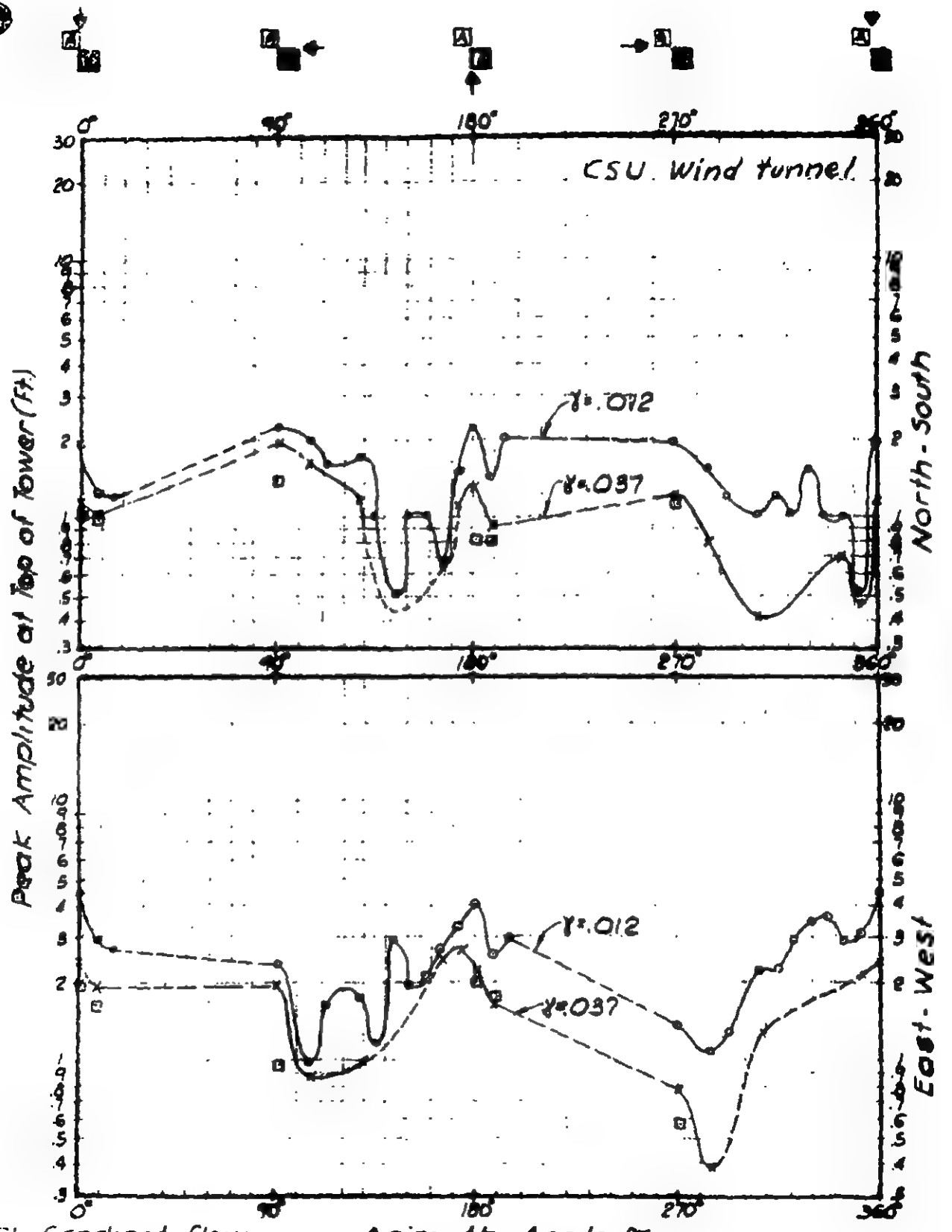
EXP 006969



NPL Gradient flow
V = 100 m.p.h.

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 27b

VARIATION OF MAXIMUM SWAY AMPLITUDE
WITH WIND DIRECTION AND DEGREE OF DAMPING
TOWER A

FIG. 28a

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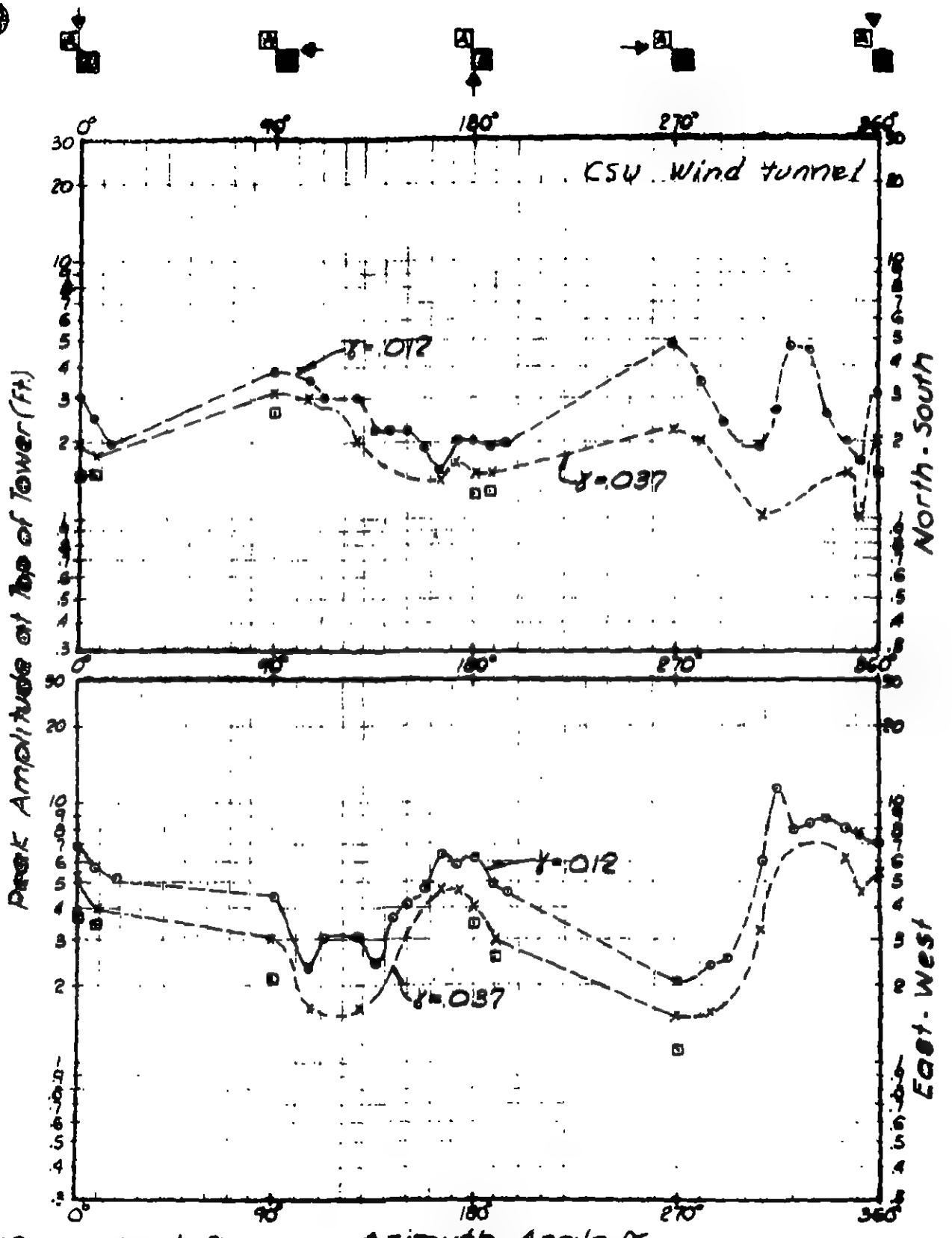
EXP 006971



NPL gradient flow
V = 125 m.p.h.

Azimuth Angle α

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 28b

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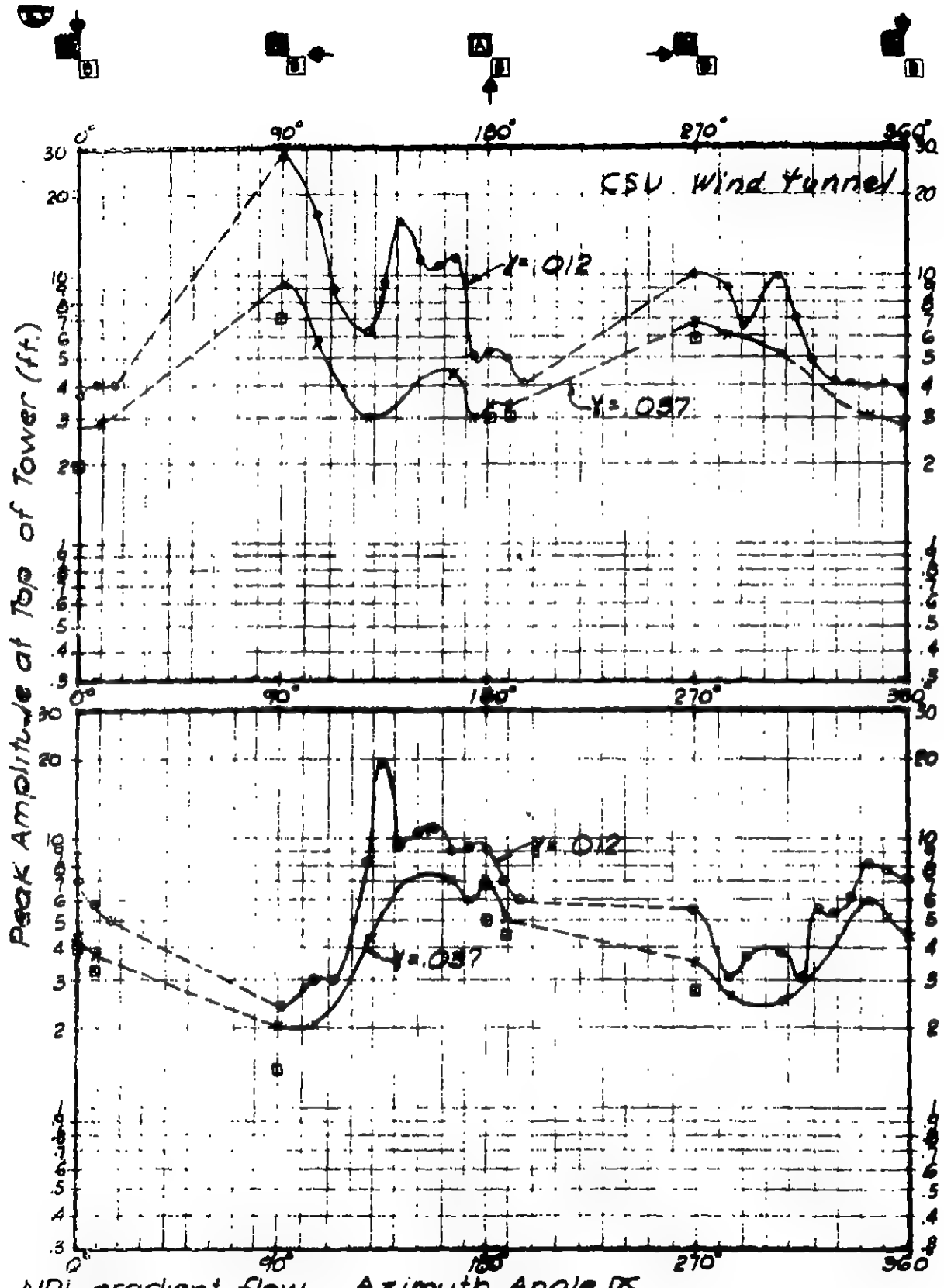
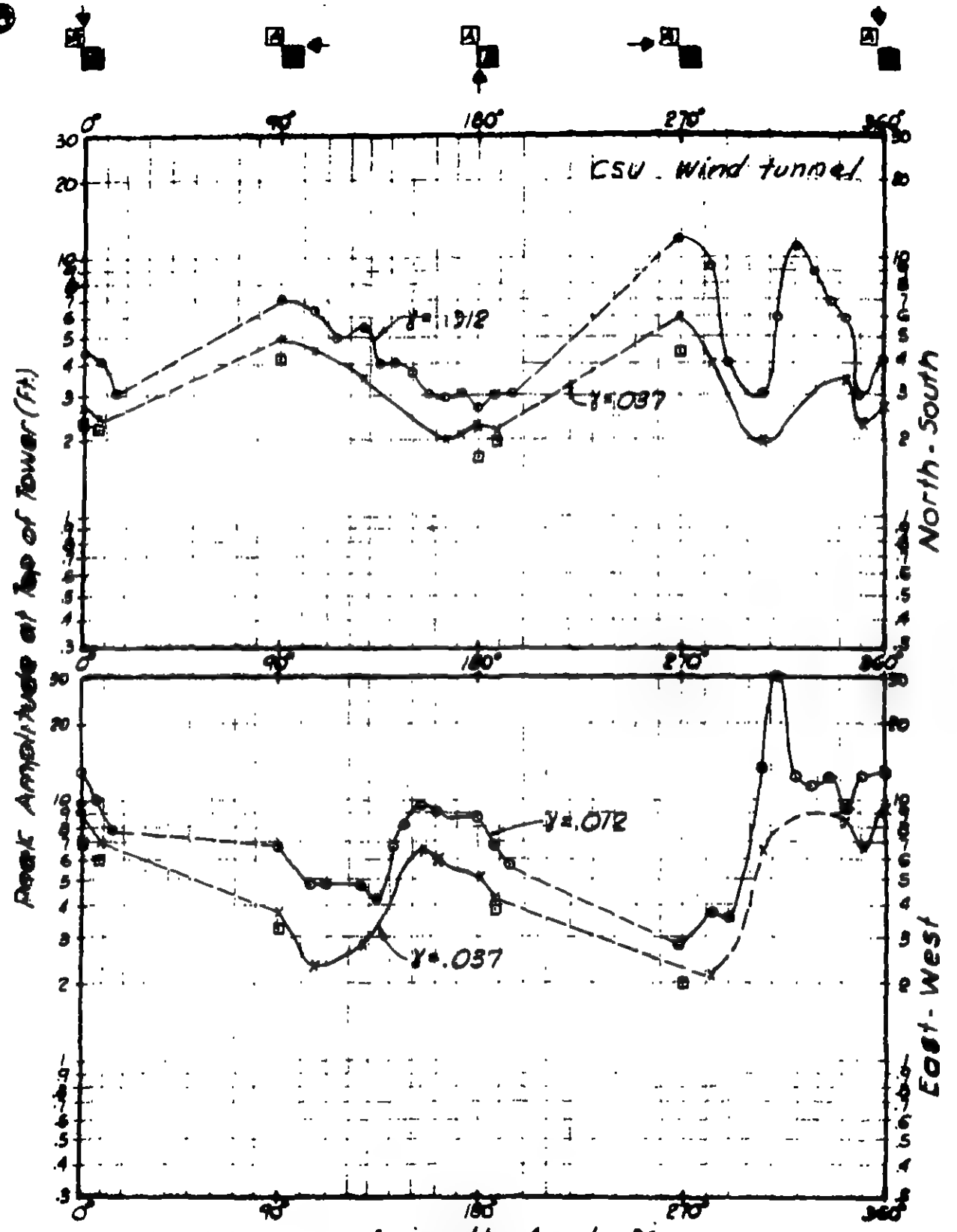
EXP 006972



TOWER A

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 29a



NPL gradient flow
V = 150 m.p.h.

TOWER B

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

FIG. 29b

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EXP 006974

Three turbulent boundary layer flows are available for comparison, these being the southeast and southwest models of New York and the NPL flow generated by a grid. For the CSU models two frequencies were available, designated the high frequency (HF) and low frequency (LF). Comparison of the tests reveals the following:

1. In all tests the response increased monotonically with increasing wind velocity without any apparent peaks of response.
2. At velocities below 150 mph the response of the NYSE test and the NPL tests were qualitatively similar and about the same magnitude. At wind velocities in excess of about 150 mph the largest response was found with the NPL tests. At velocities of the order of 175 mph the NPL results are significantly larger. This response with the NYSW was less than both the NPL and NYSE but qualitatively similar.
3. Comparison of the high frequency and low frequency tests indicates in the NYSW case that higher response occurs with the high frequency models: the NYSE indicates the opposite however. This opposing tendency in the two models tends to dispel the likelihood of a velocity influence. It should be recognized that it is only possible to compare the responses at the lower velocities. The amplitudes on the oscillograph charts are then small in the low frequency case which offers some difficulty in exact measurement. The differences in the amplitudes between high and low frequency tests lie within the tolerable accuracy of the test results.

4. The largest responses in all tests are found to be with the wind from the following directions:

Tower A		Tower B	
E-W (stiff direction)	N-S (weak direction)	E-W (weak direction)	N-S (stiff direction)
0°, 150°, 180°	90°	0°, 180°, 330°	270°

Comparison of the test results for A_{N-S} for 90° (the most severe oscillation) with the NYSE and NYSW models of New York and the NPL tests are shown in Fig. 30. Selections of the chart traces for these directions are shown in Figs. 7 and 8. Fig. 31 shows a run with NYSW in which the damping was significantly lower than in the other tests. This particular run had to be discontinued owing to the very large increase amplitude at approximately 140 mph.

Fig. 31 shows a comparison of the A_{N-S} response for 90° and the B_{N-S} response for 270° as a function of the reduced wind velocity (V/nD) based on the frequency of the motion considered. This shows the equivalence of the results for complementary wind directions, an assumption made above in estimating the response of the NPL models for angles of attack greater than 180°, for which no tests were available.

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EXP 006976

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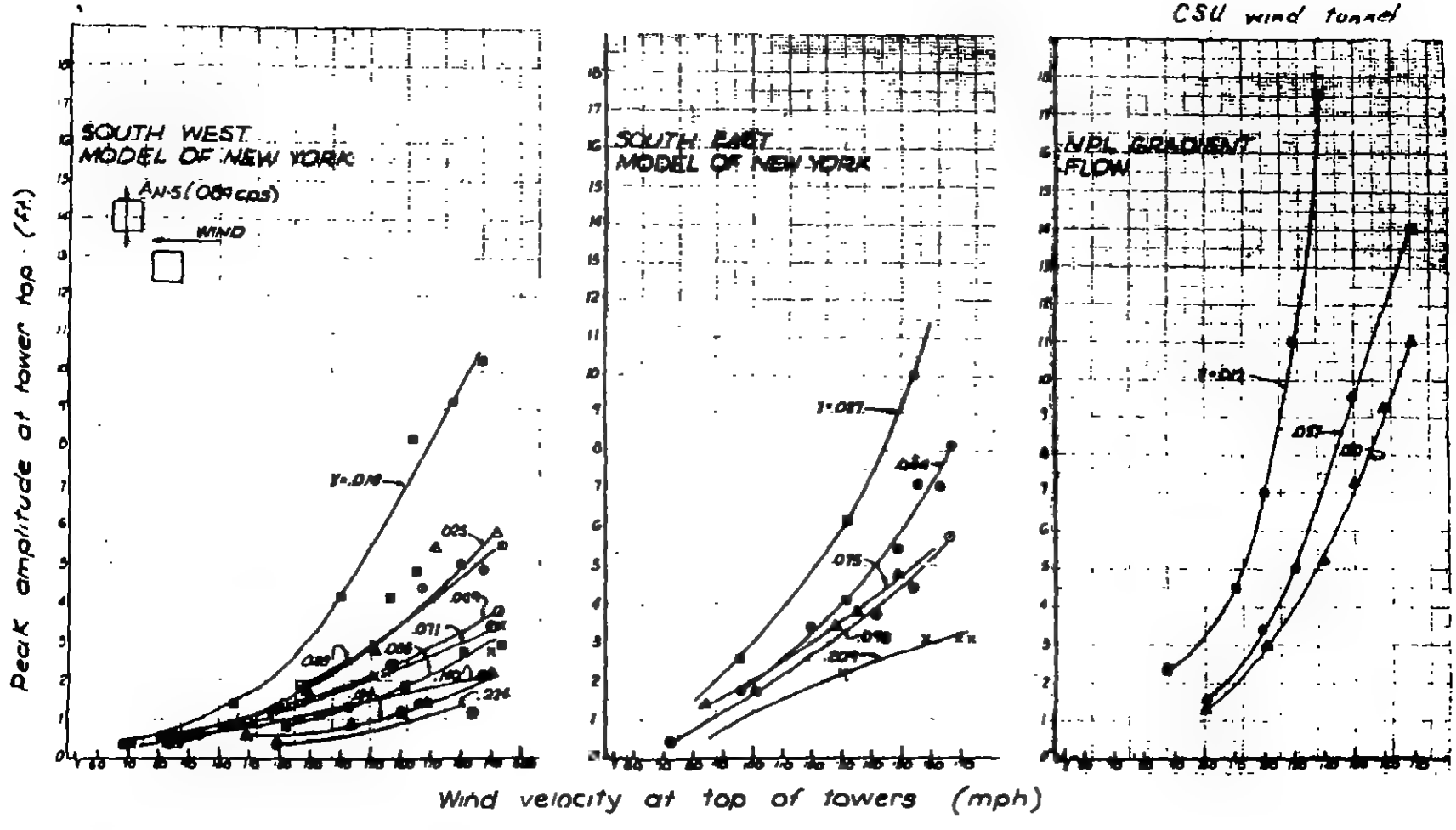

COMPARISON OF THE VARIATION OF THE N-S AMPLITUDE OF TOWER A IN EAST WIND WITH WIND VELOCITY FOR DIFFERENT DEGREES OF DAMPING AND FLOW CONDITIONS.

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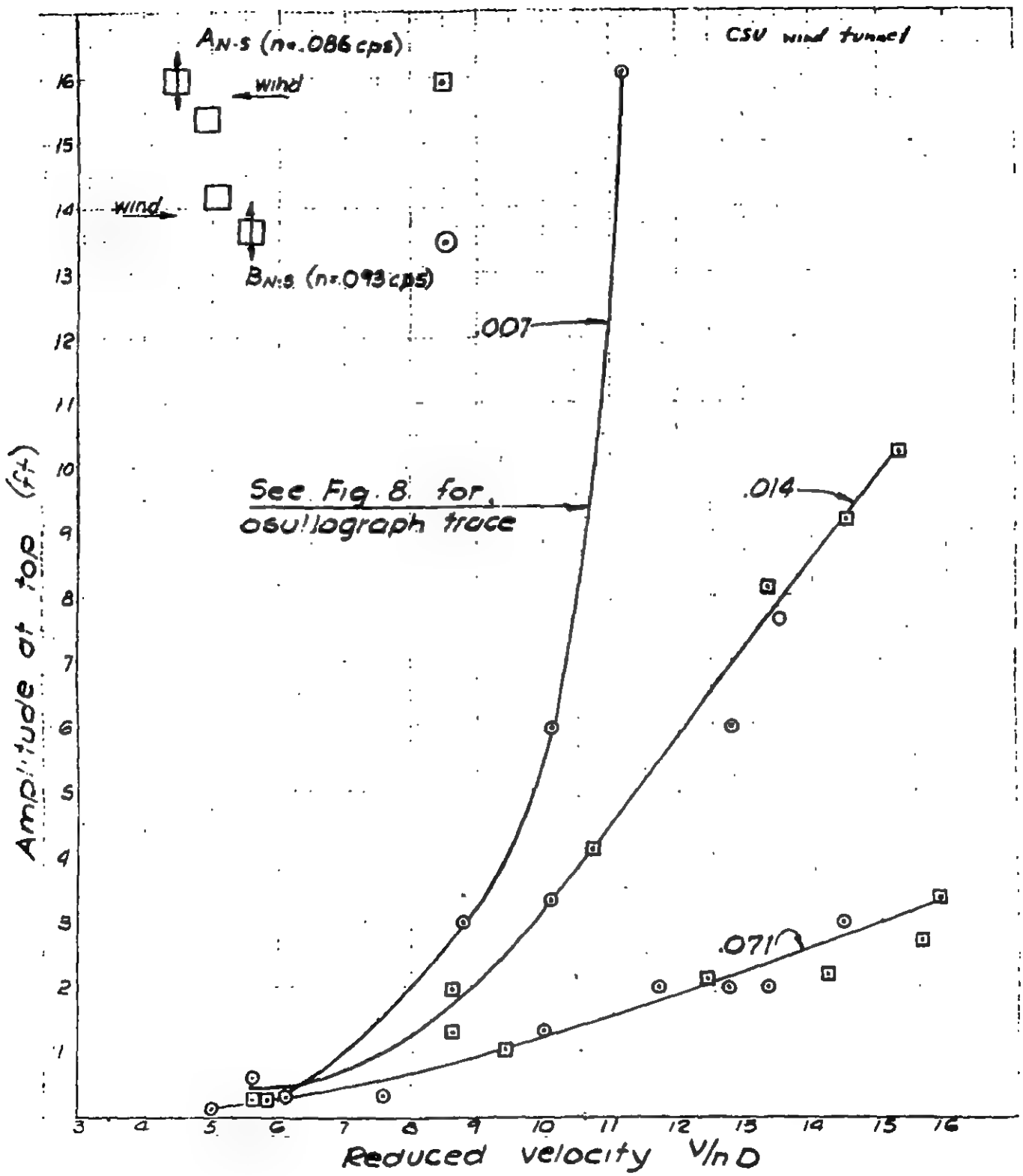

COMPARISON OF N-S RESPONSE OF TOWER A IN AN EAST WIND WITH N-S RESPONSE OF TOWER B IN WEST WIND. REDUCED VELOCITY REFERRED TO FREQUENCY OF MOTION (SW MODEL OF NY-LF)

FIG. 31

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EXP 006978

Discussion

To explain the response and to develop an understanding of the mechanisms causing dynamic excitation of the towers of The World Trade Center it is desirable first to define a plausible model to account for the behaviour and second, from this model to make theoretical predictions of the response which can be compared with the observed response. Compatability of the theoretical and observed responses then constitutes a circumstantial proof of the validity of the model. This is attempted in this section. It follows along the lines discussed in a paper by Davenport (1966) and presented at the Symposium on Tall Buildings at Southampton.

The response of The World Trade Center towers to the wind appears to be governed by three principal aerodynamic factors:

1. The magnitude of the effective turbulence forces induced by the flow approaching the model.
2. The magnitude of the effective forces induced by vortex shedding and turbulence in the structure's own wake.
3. The effective aerodynamic damping and coupling forces generated by the motion of the tower through the air flow.

Further factors, associated with the structure itself, which affect the response are:

1. The effective mass,
2. The effective stiffness,
3. The mode of vibration, and
4. The mechanical damping.

A further explanation and definition of the aerodynamic factors is given below.

Turbulence in the oncoming flow comprises velocity fluctuations in both the longitudinal direction as well as in the vertical and horizontal transverse directions. Each fluctuation of velocity is of finite size and, it may be assumed, therefore, affects only a local region of the structure. The longitudinal fluctuations give rise to fluctuations in the effective velocity pressure approaching the structure while the lateral fluctuations affect the relative angle from which the wind approaches and, thereby, changes the effective aerodynamic force coefficent.

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EXP 006980

Generally speaking, the force in the x direction on a section of a structure can be expressed by the equation

$$F_X = \frac{1}{2} \rho V^2 C_{F_X}(\alpha) \qquad (1)$$

in which $\frac{1}{2}\rho V^2$ is the local velocity pressure and $C_F(\alpha)$ the aerodynamic force coefficient which depends on the angle of attack α. If the longitudinal and lateral changes in velocity are δu and δv relative to the mean velocity $\bar{V}$ then the change in force δF_X on the structure can, with reference to Fig. 32, be written

$$\delta F_X = \frac{1}{2} \rho \bar{V}^2 \left\{ \frac{dC_{F_X}}{d\alpha} \cdot \frac{\delta v}{\bar{V}} + 2 C_{F_X} \frac{\delta u}{\bar{V}} \right\} . \qquad (2)$$

Similarly

$$\delta F_Y = \frac{1}{2} \rho \bar{V}^2 \left\{ \frac{dC_{F_Y}}{d\alpha} \cdot \frac{\delta v}{\bar{V}} + 2 C_{F_Y} \frac{\delta u}{\bar{V}} \right\} \qquad (3)$$

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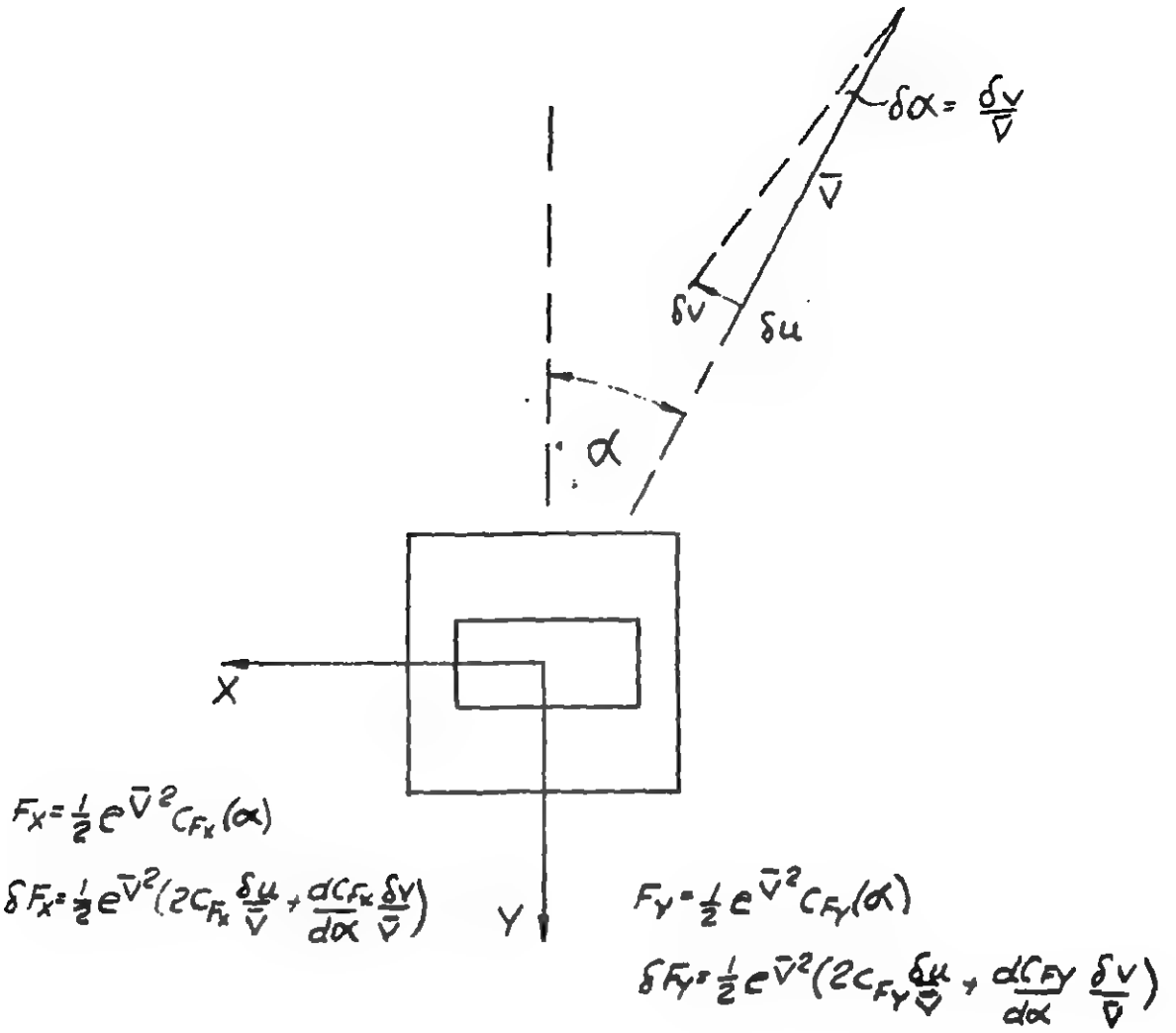
EXP 006981



RESPONSE OF SINGLE TOWER TO FLUCTUATIONS IN VELOCITY

FIG. 32

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EXP 006982

The validity of these relationships is dependent on three basic assumptions. The first is that the fluctuations $\int u$ and $\int v$ are small compared to the mean velocity $\overline{V}$; second that the coefficients ${}^{C}F_{x}$ and ${}^{C}F_{y}$ are relatively insensitive to the time rates of change of $\int u$ and $\int v$. The latter may be termed a quasi-steady assumption. The third assumption is that local changes in force on the structure are affected only by local changes in velocity. In the case of turbulence, where the fluctuations in velocity are space and time dependent, there may be interaction effects implying that changes in velocity at a point may have effects on the aerodynamic force at remote points. For relative slender structures, however, such as the towers of The World Trade Center, the quasi-steady assumption seems reasonable as a first approximation.

The value of these equations is that they provide the means for expressing the force fluctuations on a body in terms of the velocity fluctuations in the flow. The latter can be described with reasonable assurance in many circumstances as has been shown by Davenport (1963).

The phenomenon of vortex shedding by a cylinder in uniform steady flow is relatively well understood and has been the subject of considerable research. With a bluff object such as a square cylinder, the wake boundary emanates from the forward sharp edges and spreads out on either side of the after body as shown in Fig. 33. The flow characteristics within this wake region are generally rotational and have fluctuating characteristics. In particular there is a tendency for vortices to be shed from either side of the body

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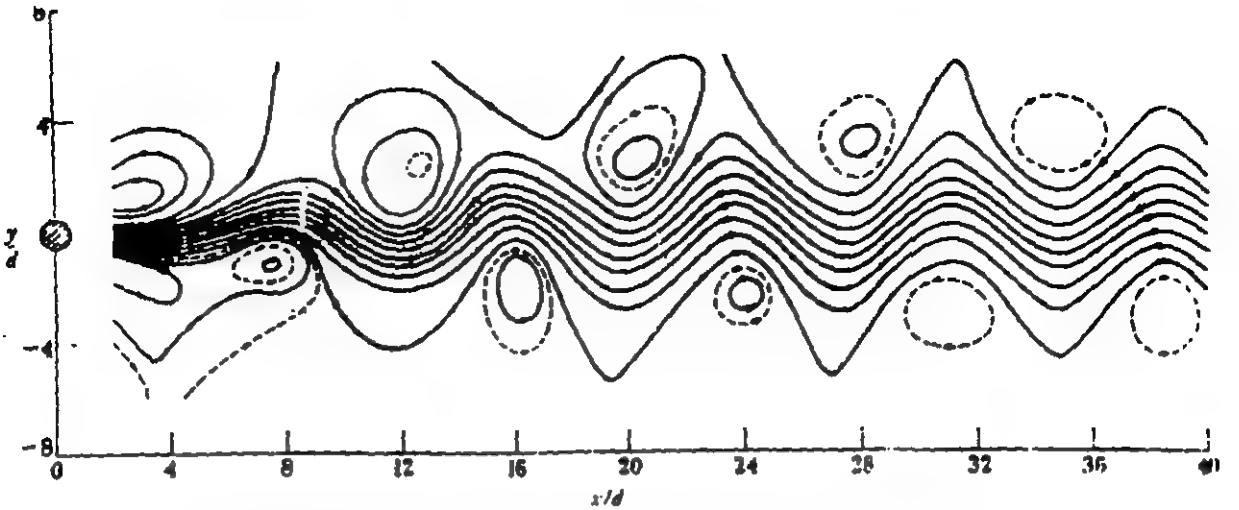
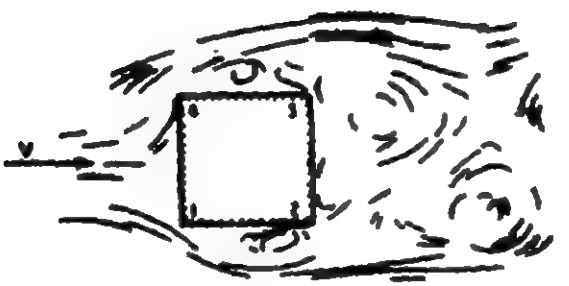


BEHIND CIRCULAR CYLINDER
(AFTER KOVASZNAY)



BEHIND SQUARE CYLINDER
(AFTER PARKINSON)

DIAGRAMS OF FLOW PATTERN BEHIND BUFF CYLINDERS SHOWING VORTEX STREET FORMATION IN LAMINAR FLOW

FIG. 39

emanating from the leading edges of the structure as in Fig. 33.

The frequency of shedding of these vortices is given by the relation

$$\frac{nd}{\bar{V}} = S \qquad (4)$$

where d is the diameter of the body V is the velocity and S is a dimensionless number known as the Strouhal number. For the infinite square cylinder S has the value of approximately 0.13. This fluctuation in vorticity about the structure gives rise to lateral lift forces on the structure which have the same frequency. This phenomenon also tends to produce fluctuating forces in the direction of the flow; they are however of a much smaller magnitude and at twice the frequency of the lift fluctuations.

This behaviour described above holds for uniform flow but not necessarily for turbulent or sheared flow. The effect of turbulence on the character of the vortex shedding is as yet imperfectly understood although investigations carried out on The World Trade Center and by Vickery (1965) appear to shed some light on this question. These studies have also shown some of the effects of gradient flow, in which there is a shearing of the wind.

Aerodynamic Damping and Coupling Forces

When a body oscillates in an airstream, the motion of the body in general produces changes in the magnitude and direction of the wind relative to the body. These changes can give rise to forces which can tend to either counteract or to reinforce the motion. Forces can also be induced which are not in the direction of motion. For small amplitudes of oscillation these forces are generally proportional to the velocity and, therefore, constitute either damping or coupling forces depending on the relationship of the motion and force direction. Negative damping forces (tending to reinforce the motion) are known to give rise to forms of aerodynamic instability of conductor cables known as "galloping". Parkinson (1965) has studied the instability of the square cylinder oscillating in a transverse mode.

Some discussion of the response in the transverse mode is appropriate to explain the instability phenomenon. Fig. 34 shows a square cylinder with the wind blowing normal to a face. If the cylinder has a velocity $\dot{X}$ to the left *(+ve)*, the relative angle of the wind changes by a small angle $\delta\alpha = \frac{\dot{X}}{\bar{V}}$. Fig. 35 shows the force coefficient ${}^{C}F_{X}$, the x direction *(+ve* to the left*)*, for small angles of attack as measured by Parkinson (1965). The resulting force on the body in the $\mathcal{X}$ direction for this small angle change is given by

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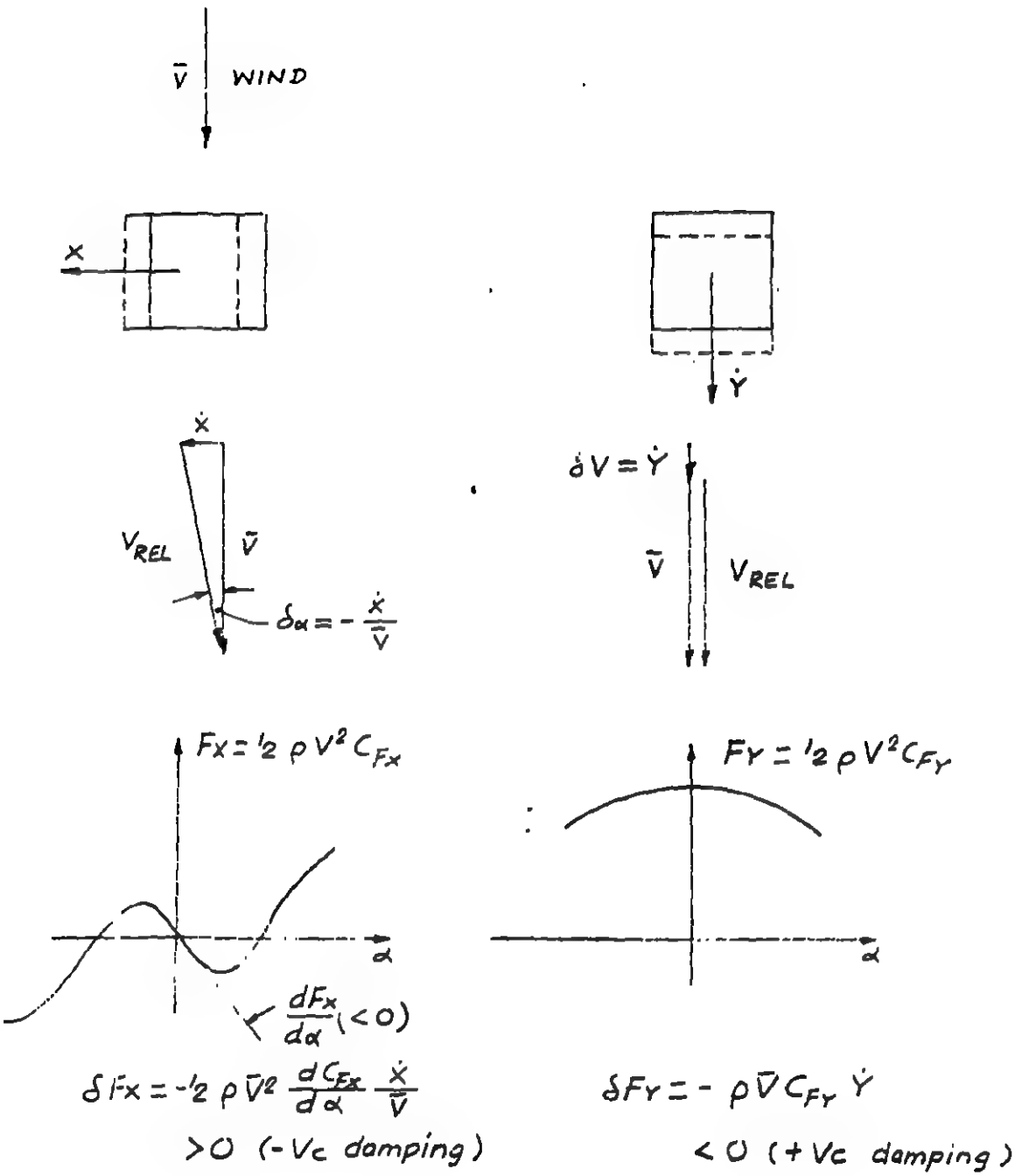
EXP 006986



DIAGRAMS SHOWING VARIATION IN AERODYNAMIC FORCE ON A BODY DUE TO MOTION OF BODY

FIG 34

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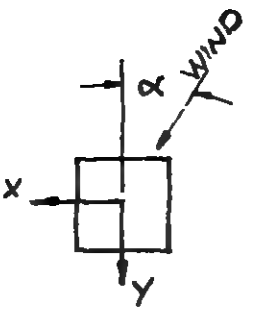
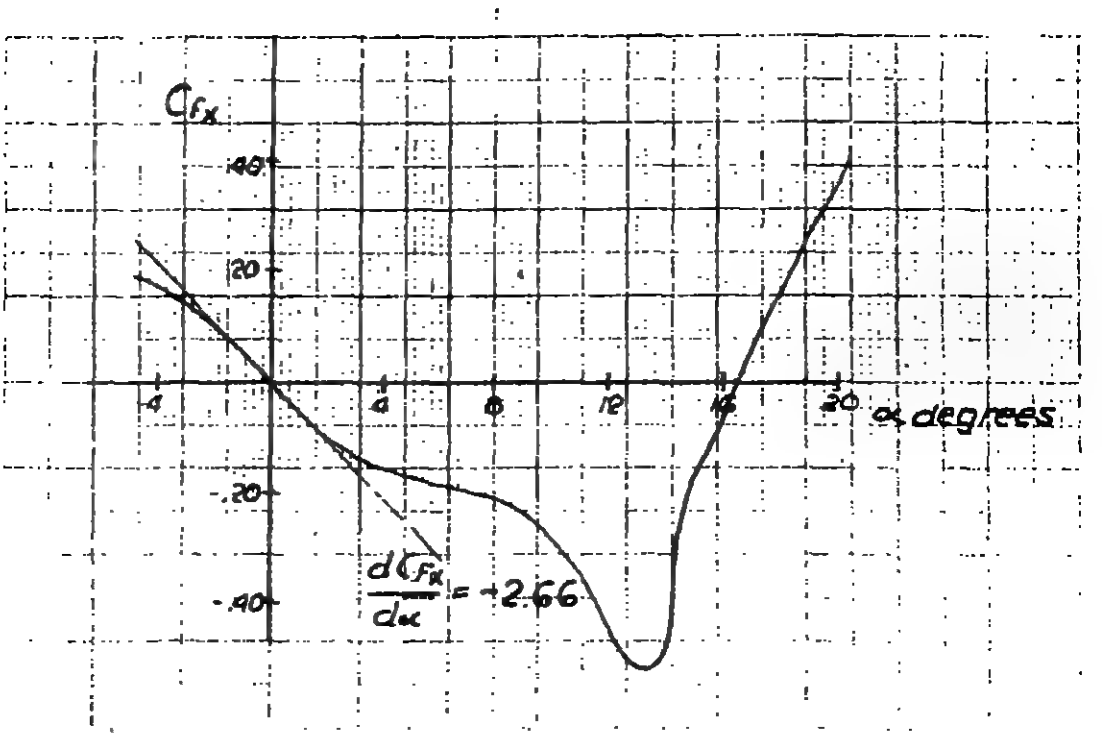
EXP 006987





PARKINSONS[1] MEASUREMENTS OF THE VARIATION OF THE LATERAL FORCE COEFFICIENT WITH INCIDENCE FOR AN INFINITE SQUARE CYLINDER.

FIG 35

CONFIDENTIAL

EXP 006988

$$\delta F_X \approx \frac{1}{2} e^{\bar{V}^2} \frac{dC_{F_X}}{d\alpha} \delta\alpha$$

$$= -\frac{1}{2} e^{\bar{V}} \frac{dC_{F_X}}{d\alpha} \dot{X}$$

Since, in this instance, the slope $\frac{dC_{F_X}}{d\alpha}$ is negative, the resulting force δF_X is +ve thus tending to reinforce the motion. This force is proportional to the velocity of the cylinder and thus constitutes a damping force; because it reinforces the motion it is a negative damping force.

If, in addition, the cylinder in Fig. 34 has a small velocity $\dot{Y}$, (+ve downward) as shown, the relative velocity in the Y direction changes by the amount $\delta V = -\dot{Y}$. The change in force resulting from this motion is

$$\delta F_Y = \frac{d}{d\bar{V}} \left\{ \frac{1}{2} e^{\bar{V}^2} C_{F_Y} \right\} \delta V = -e^{\bar{V}} C_{F_Y} \dot{Y}$$

Since C_{F_Y} is positive, this change in force is such as to oppose the motion, is proportional to the velocity of the cylinder and constitutes positive aerodynamic damping.

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The aerodynamic characteristics giving rise to the possibility of both positive and negative aerodynamic damping on the square cylinder are also present in The World Trade Center tower and also other structures such as the Empire State Building. Fig. 36 shows the variation of the aerodynamic force coefficients on the Empire State Building with angle of attack as determined from the wind tunnel tests by Dryden and Hill (1933). The negative slope of this curve at the origin implies that the aerodynamic damping is negative when the wind is blowing normal to a face. Figs. 37 and 38a and b indicate the same is found to be true for The World Trade Center towers.

More general expressions for damping and coupling forces acting on a section can be derived from the diagram in Fig. 39. The changes in force on a square section in a mean velocity $\bar{V}$ due to motions $\dot{X}$ and $\dot{Y}$ along the two axes are found to be

$$\delta F_X = \frac{1}{2}\rho \bar{V} \left[\left\{ \frac{dC_{F_X}}{d\alpha} \sin\alpha - 2C_{F_X} \cos\alpha \right\} \dot{Y} + \left\{ -\frac{dC_{F_X}}{d\alpha} \cos\alpha - 2C_{F_X} \sin\alpha \right\} \dot{X} \right] \quad (5)$$

$$\delta F_Y = \frac{1}{2}\rho \bar{V} \left[\left\{ \frac{dC_{F_Y}}{d\alpha} \sin\alpha - 2C_{F_Y} \cos\alpha \right\} \dot{Y} \left\{ -\frac{dC_{F_Y}}{d\alpha} \cos\alpha - 2C_{F_Y} \sin\alpha \right\} \dot{X} \right] \quad (6)$$

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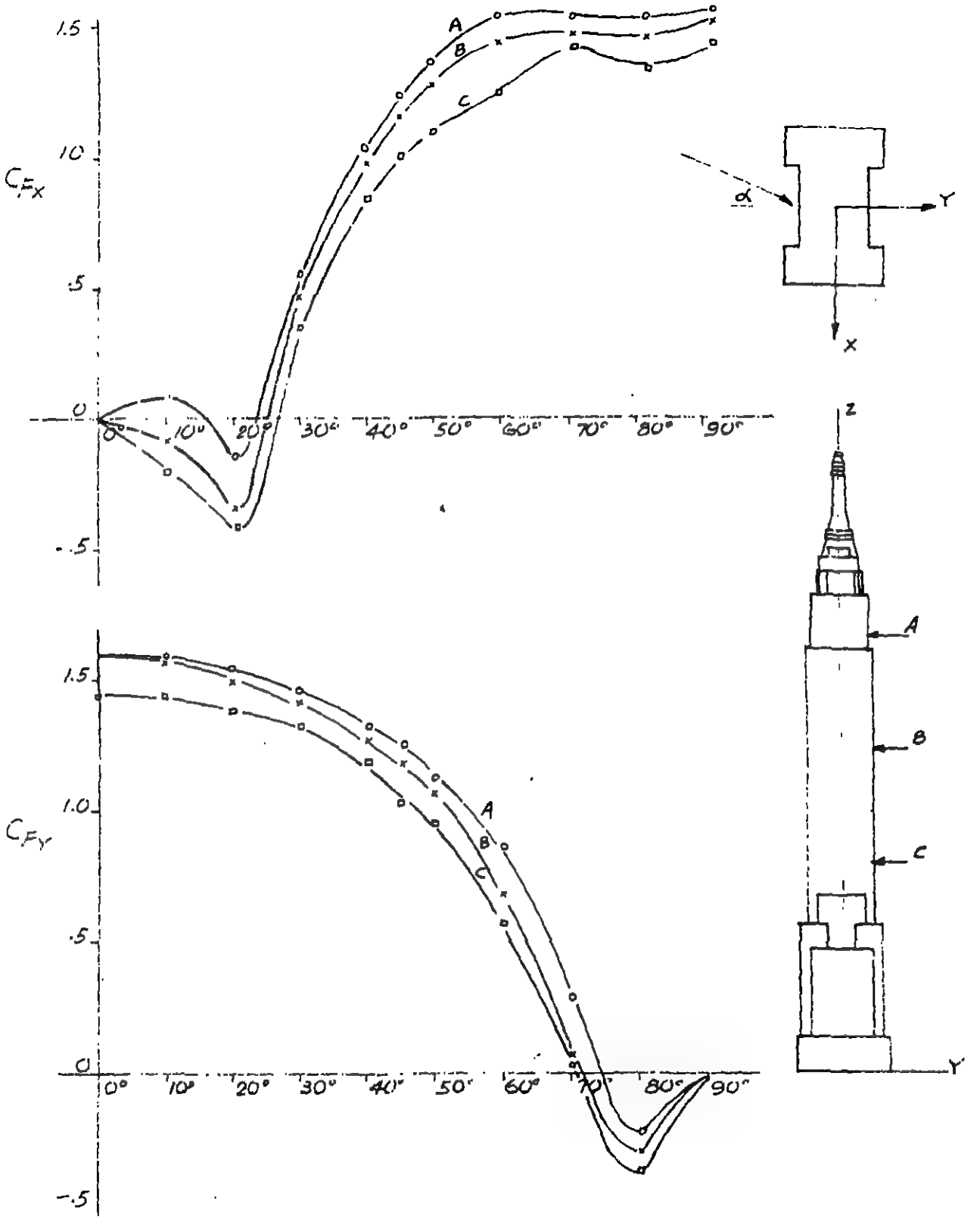

FIG. AERODYNAMIC FORCE COEFFICIENTS ON EMPIRE STATE BUILDING IN UNIFORM FLOW (AFTER DRYDEN & HILL)

FIG 3G

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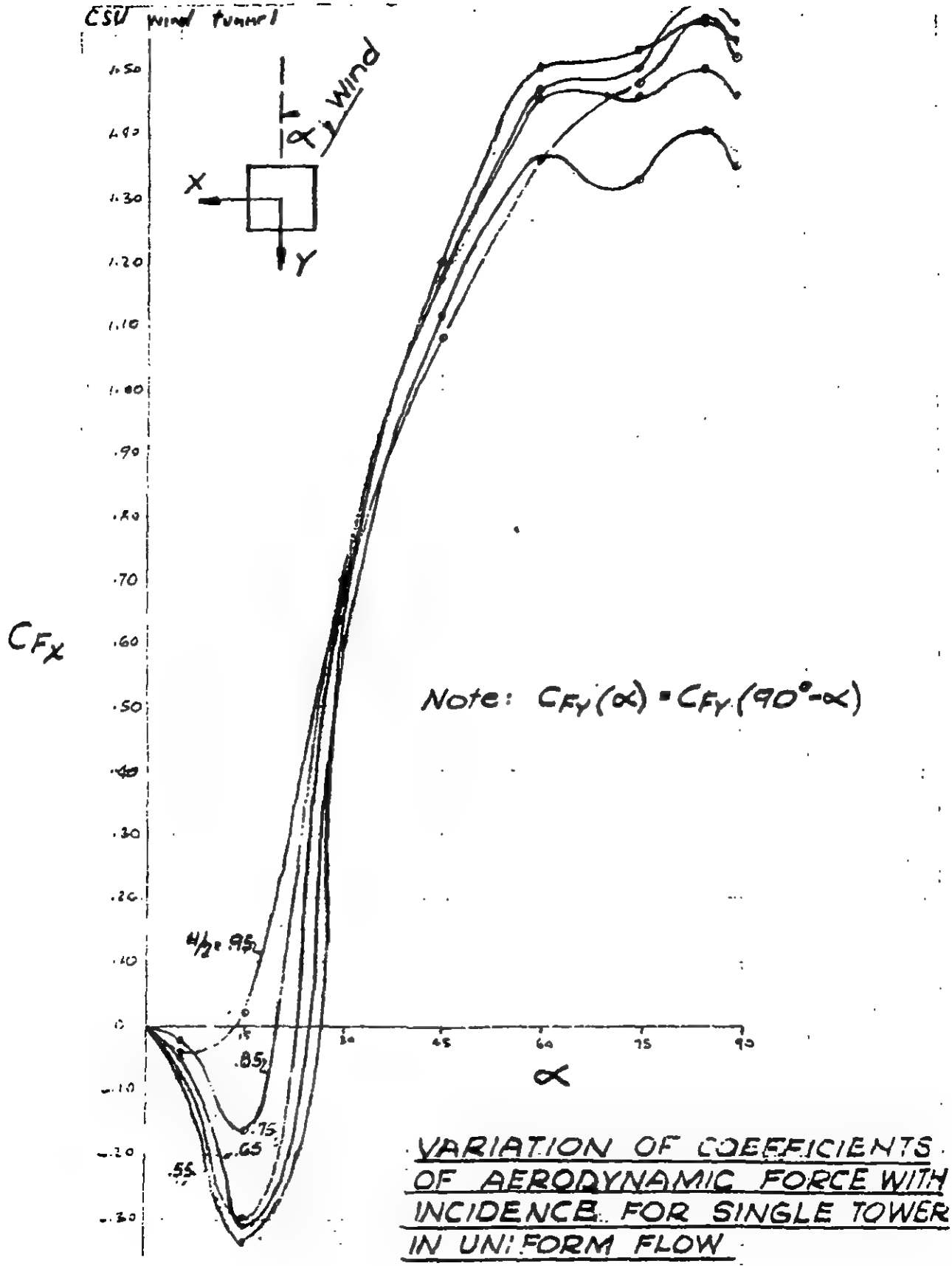

VARIATION OF COEFFICIENTS OF AERODYNAMIC FORCE WITH INCIDENCE FOR SINGLE TOWER IN UNIFORM FLOW

FIG.37

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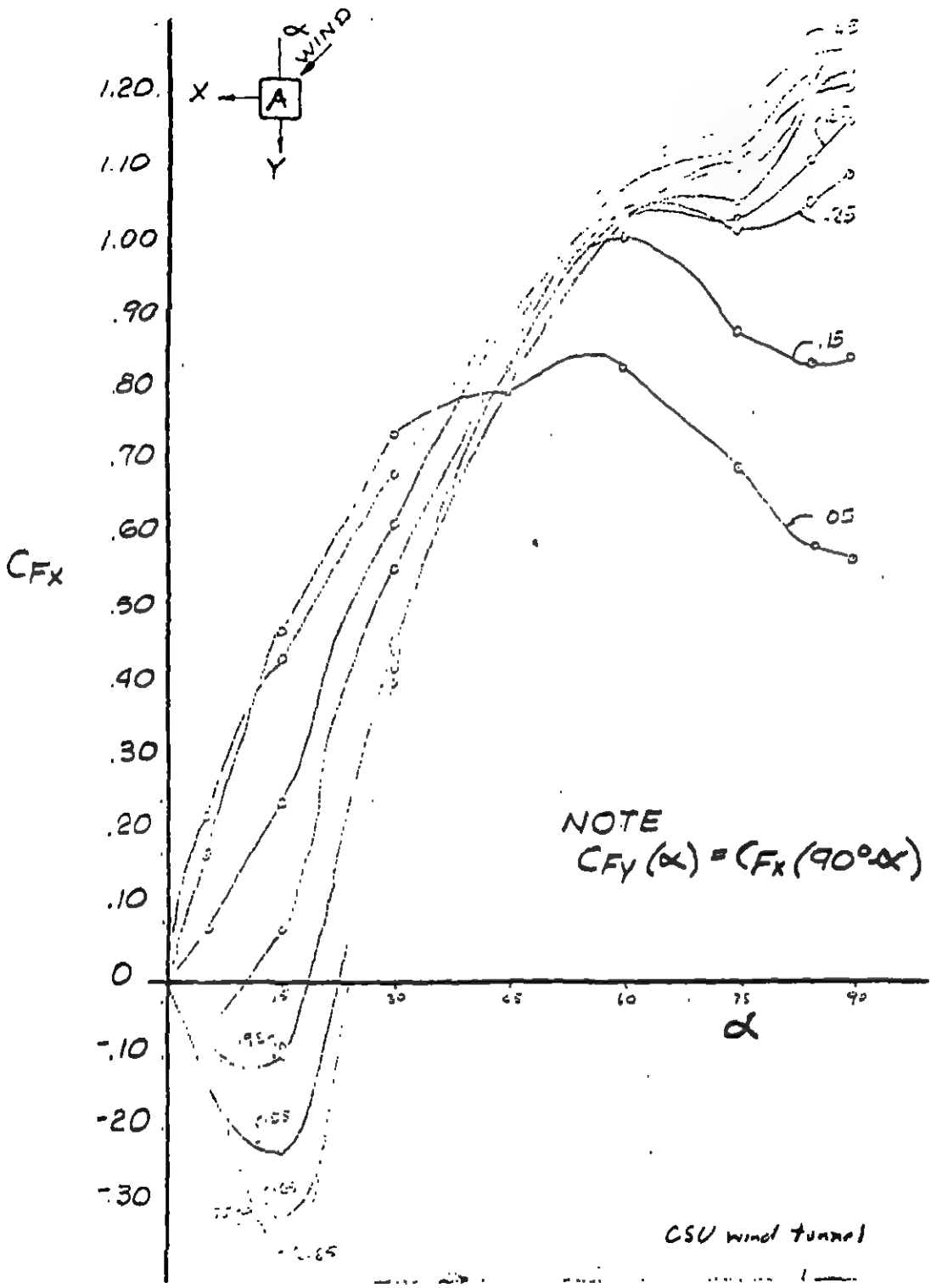
EXP 006000



VARIATION OF FORCE COEFFICIENT FOR TOWER A WITH INCIDENCE FOR VARIOUS HEIGHTS ON THE TOWERS (z/H)
NYSW - SINGLE TOWER

FIG. 38a

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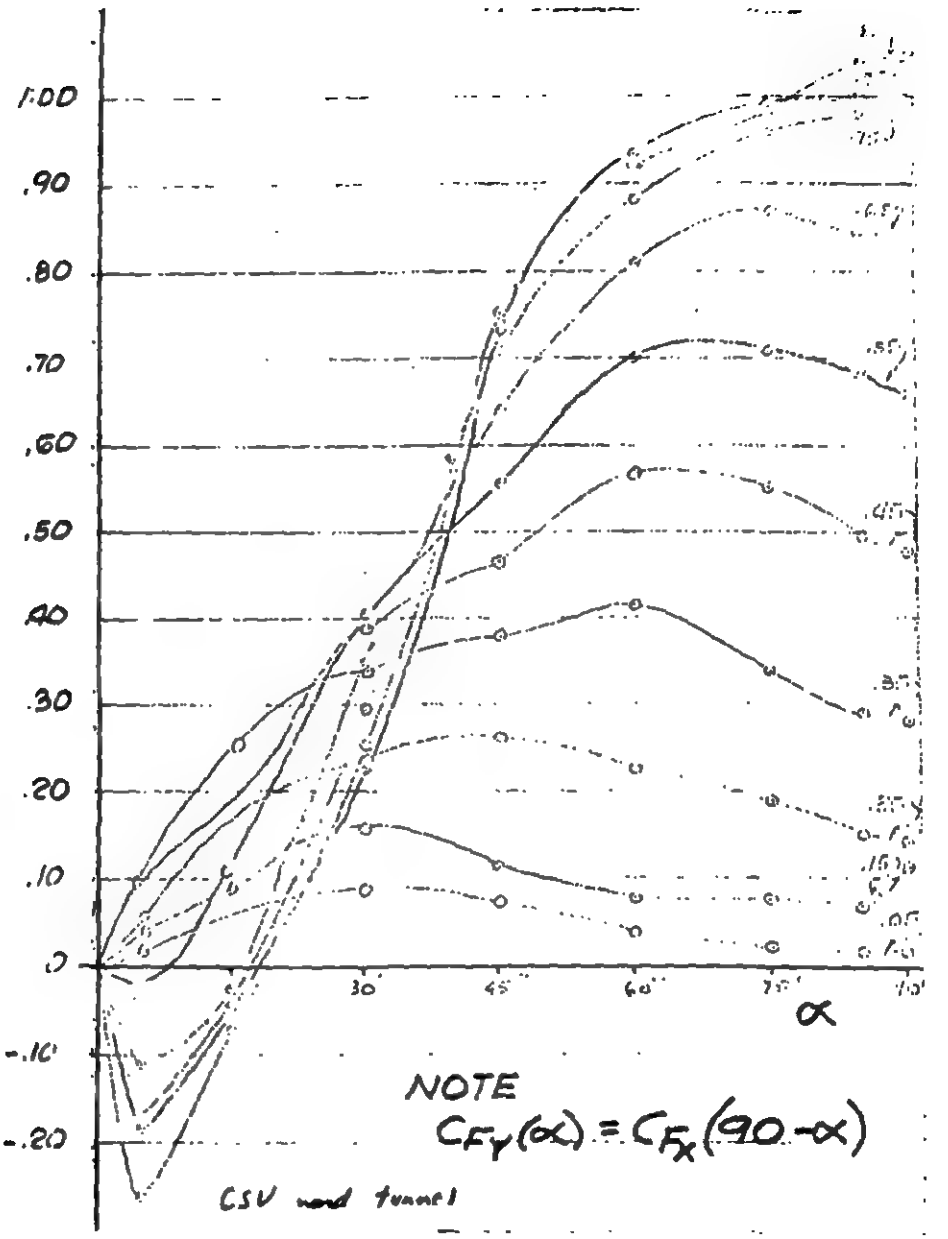
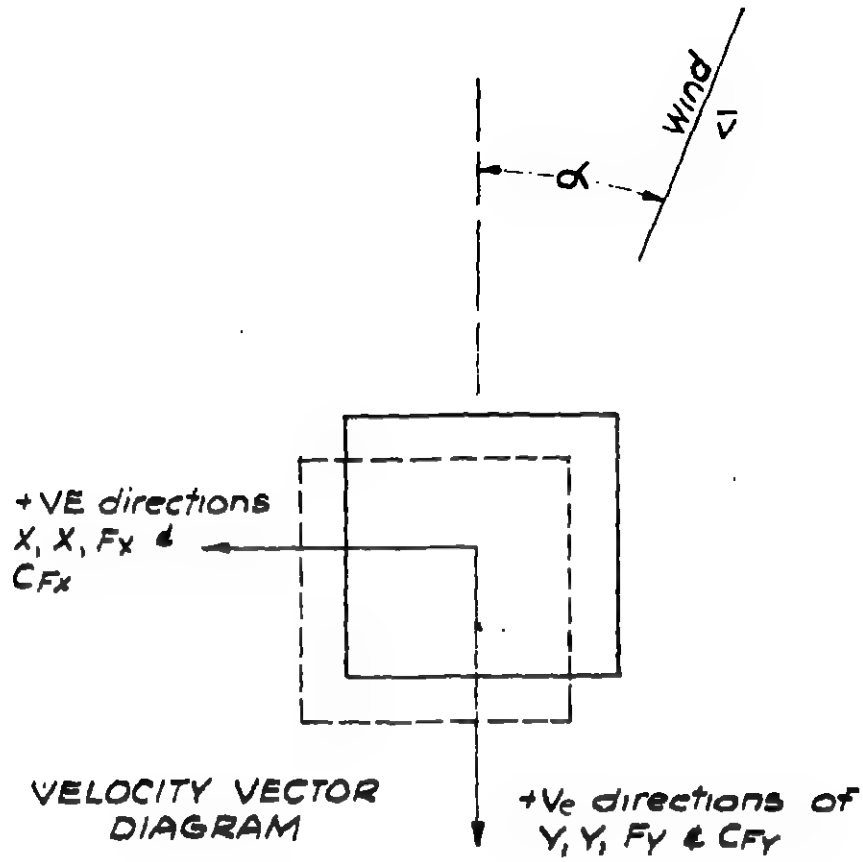
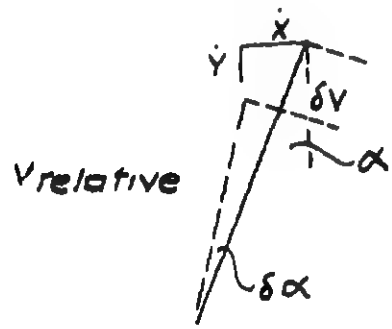


VARIATION OF FORCE COEFFICIENT FOR TOWER A WITH INCIDENCE FOR VARIOUS HEIGHTS ON THE TOWER (z/H). NYSE SINGLE TOWER.

FIG. 38b





$$\delta V = -\dot{x}\sin\alpha - \dot{Y}\cos\alpha$$

$$\delta\alpha = -\frac{1}{V}(\dot{X}\cos\alpha - \dot{Y}\sin\alpha)$$

CHANGES IN MAGNITUDE & DIRECTION OF WIND RELATIVE TO BODY DUE TO MOTION OF BODY.

FIG. 39

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EXP 006995

The negative of the first brackets in these two expressions constitute damping forces (opposing motion) and the second brackets coupling forces giving rise to motion in the perpendicular directions.

If the aerodynamic coefficients C_{F_Y} and C_{F_X} are defined in terms of a reference mean velocity $\overline{V}_o$ instead of the local mean velocity V_Z and if the mode of oscillation of the body is $\mu(Z)$, the following integrals can be defined

$$D\ (X) = \int_0^1 \frac{V_o}{V_Z}\left(\frac{dC_{F_X}}{d\alpha}\cos\alpha + 2C_{F_X}\sin\alpha\right)\mu^2\ (Z)\ dZ \tag{7}$$

$$D\ (Y) = \int_0^1 \frac{V_o}{V_Z}\left(-\frac{dC_{F_Y}}{d\alpha}\sin\alpha + 2C_{F_Y}\cos\alpha\right)\mu^2\ (Z)\ dZ \tag{8}$$

and

$$G\ (X) = \int_0^1 \frac{V_o}{V_Z}\left(\frac{dC_{F_X}}{d\alpha}\sin\alpha - 2C_{F_X}\cos\alpha\right)\mu^2\ (Z)\ dZ \tag{9}$$

$$G\ (Y) = \int_0^1 \frac{V_o}{V_Z}\left(-\frac{dC_{F_Y}}{D\alpha}\cos\alpha - 2C_{F_Y}\sin\alpha\right)\mu^2\ (Z)\ dZ \tag{10}$$

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In terms of these integrals, the equivalent critical damping ratio due to these aerodynamic forces can be shown to be

$$\gamma_{aero}(X) = \frac{1}{8\pi} \frac{\rho_{air}}{\int_0^1 \rho_{bldg}^{(z)} \mu^2(z)\, dz} \frac{\bar{V}_o}{n_o d} D(X) \qquad (11)$$

$$\gamma_{aero}(Y) = \frac{1}{8\pi} \frac{\rho_{air}}{\int_0^1 \rho_{bldg}^{(z)} \mu^2(z)\, dz} \frac{\bar{V}_o}{n_o d} D(Y) \qquad (12)$$

where

ρ_{air} is the air density (.0024) slugs/cu. ft.),

$\rho_{bldg.}$ is the effective building density (.327 slugs/cu. ft.),

n_o is the natural frequency in the direction of motion (given in Fig. 5) and,

d is the tower diameter (208 ft.).

For the World Trade Center towers, if the first mode shape is idealized as a straight line (as assumed in the model tests), with unit amplitude at the top and V_o is expressed in miles per hour, the expressions yield

$$\gamma_{aero}(X) = .000073\, V_o D(X) \qquad (13)$$

$$\gamma_{aero}(Y) = .0000645\, V_o D(Y) \qquad (14)$$

As indicated by equations (7) and (8), the values of $D(X)$ are determined by the aerodynamic coefficients $\frac{dC_F}{d\alpha}$ and C_F, weighted by the velocity ratio and the mode amplitude. A first approximation to these coefficients may be obtained from the steady pressures, with the assumption that the pressures are quasi-steady and independent of their time rate of change. This approach has been used by Parkinson (1965) in predicting the instability of the square cylinder with considerable success and accuracy; in his tests the models were at somewhat higher reduced velocities than generally considered here.

For The World Trade Center towers the variation of the coefficient C_{F_X} with azimuth for different heights on the tower are shown in Figs. 37, 38, 41 and 42. The derivative $\frac{dC_{F_X}}{d\alpha}$ at any height is given by the slopes of these curves.

Fig. 40 shows the calculation of the damping functions $D(X)$ and $D(Y)$ computed from equations (7) and (8) for the case of the single tower vibrating in the first mode with the southeast model of New York. For uniform flow and the southwest model of New York, the functions are qualitatively similar. For a wind normal to the face the values of the lateral aerodynamic damping function $D(X)$ is given by

$$D(X) = \int_0^1 \frac{V_o}{V_Z} \frac{dC_{F_X}(z)}{d\alpha} \mu^2(z)\, dz \qquad (15)$$

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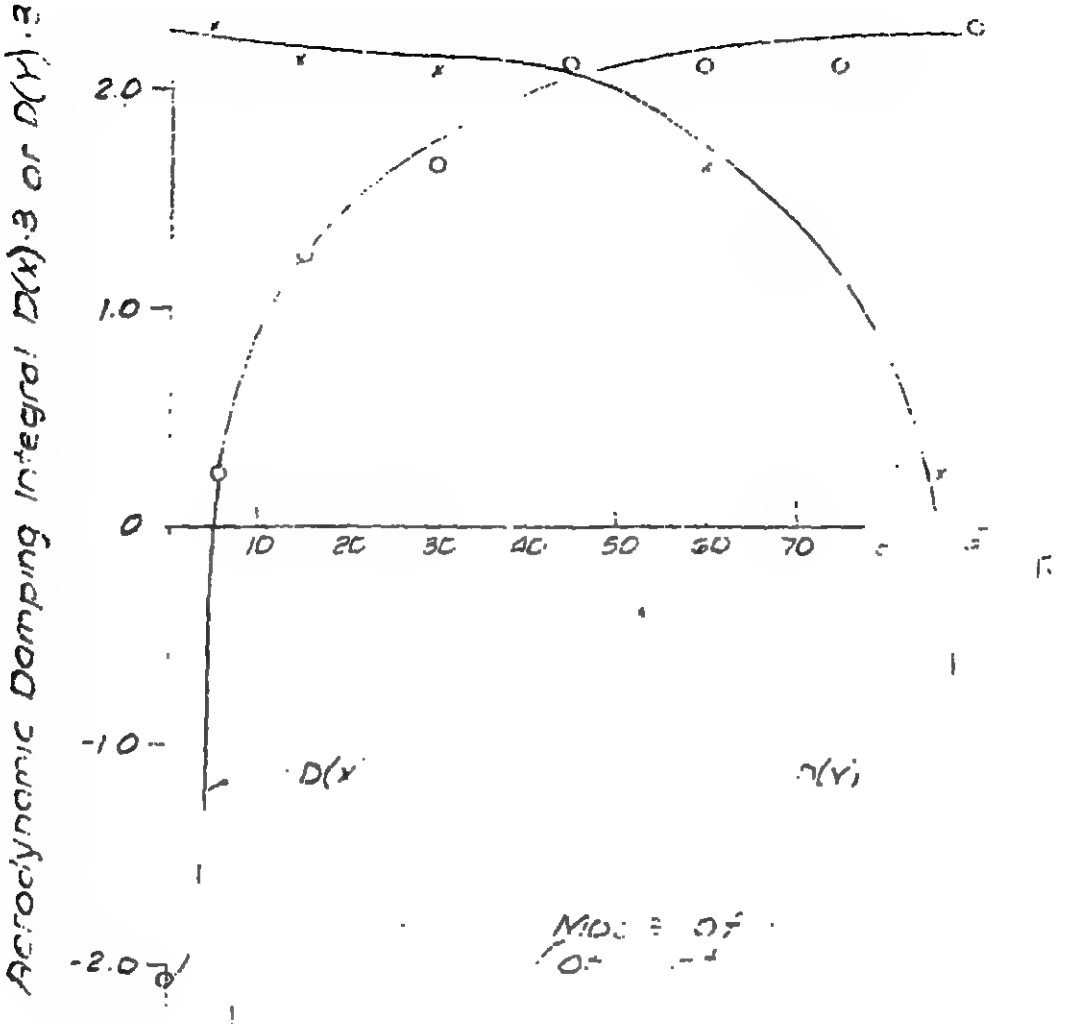
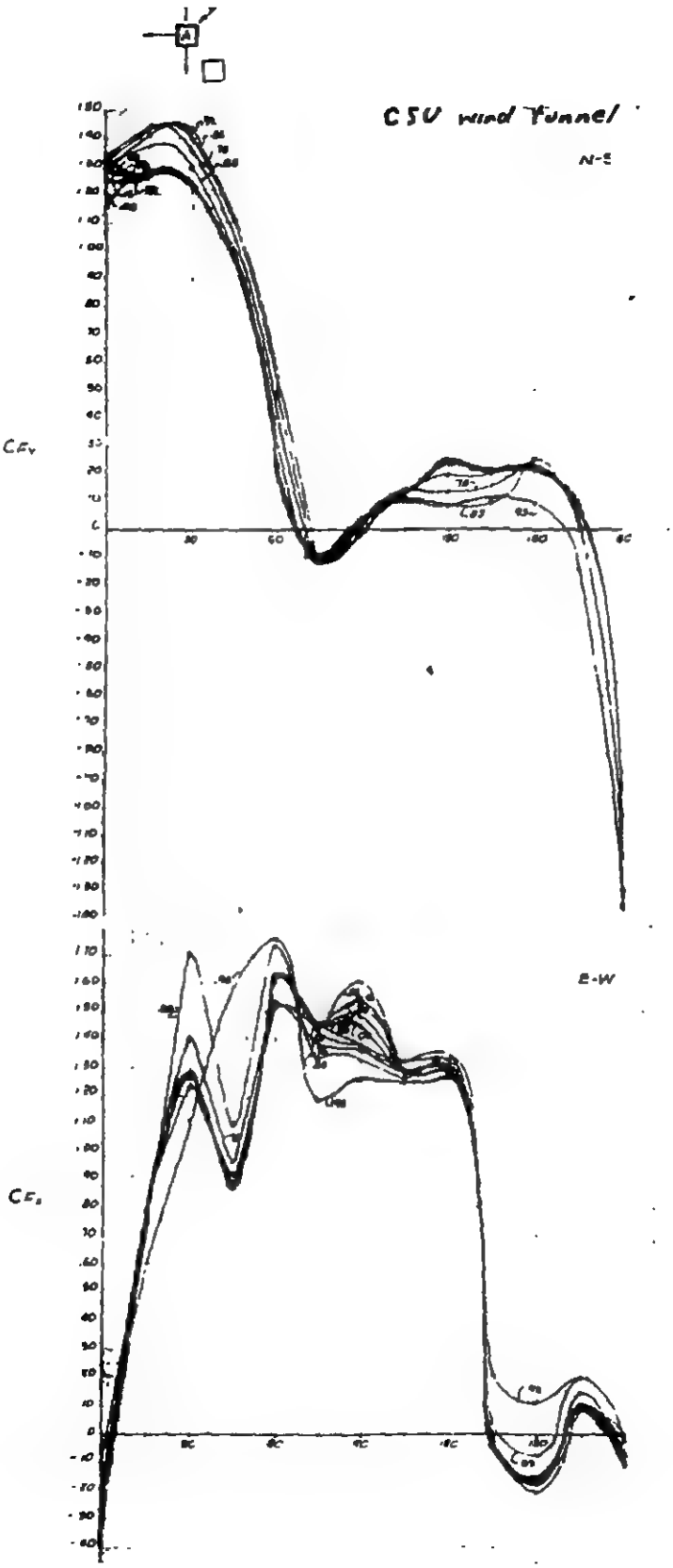

Aerodynamic Damping Integral D(x) & or D(y)
2.0
1.0
0
-1.0
-2.0
10
20
30
40
50
60
70
D(x
D(y)



VARIATION OF FORCE COEFFICIENT FOR TOWER A WITH INCIDENCE FOR VARIOUS HEIGHTS ON THE TOWER (z/H) TWIN TOWERS IN UNIFORM FLOW

FIG 41

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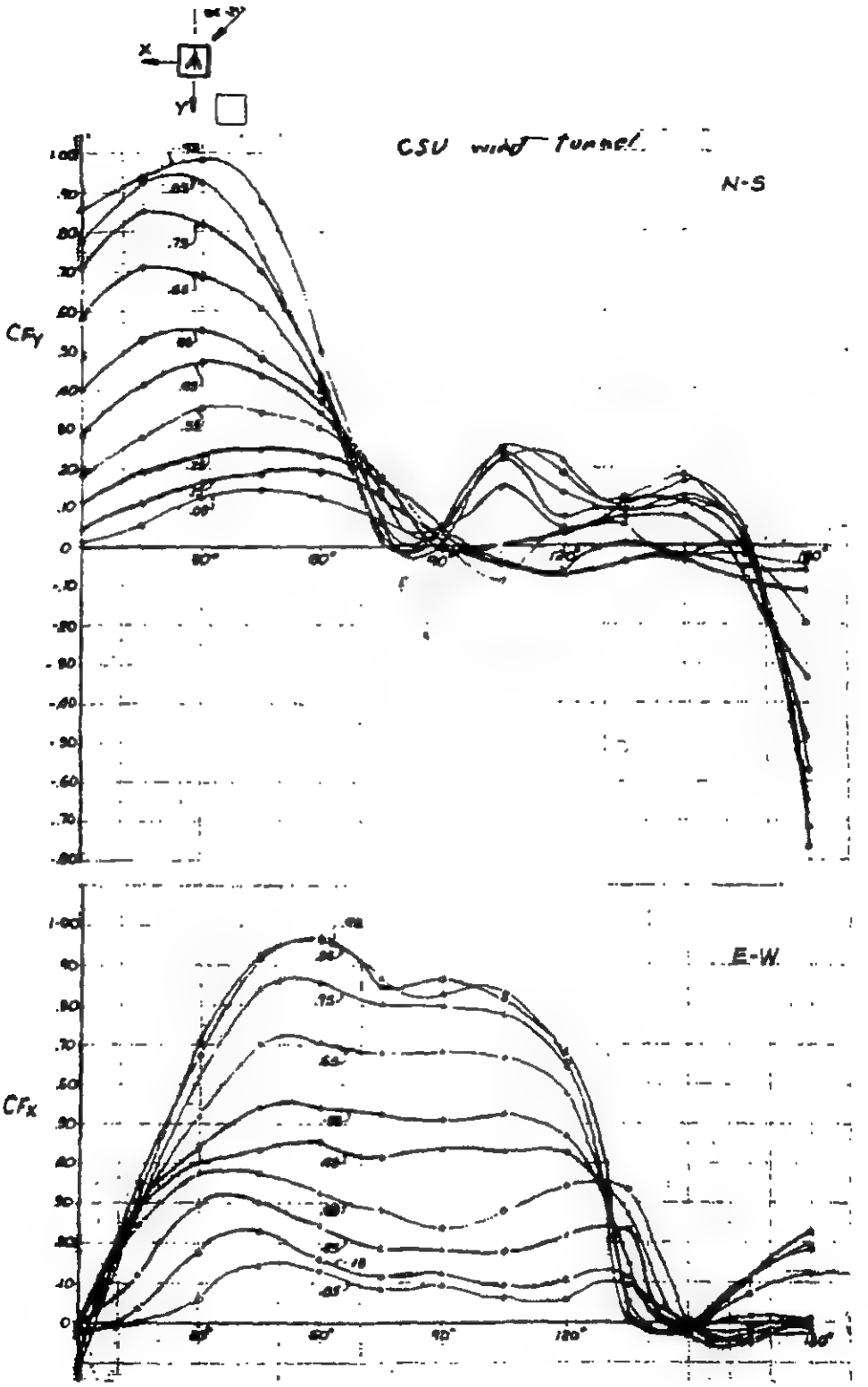
EXP 007000



VARIATION OF FORCE COEFFICIENT FOR TOWER A WITH INCIDENCE FOR VARIOUS HEIGHTS ON THE TOWER (Z/H).
NYSE TWIN TOWERS

FIG. 42a

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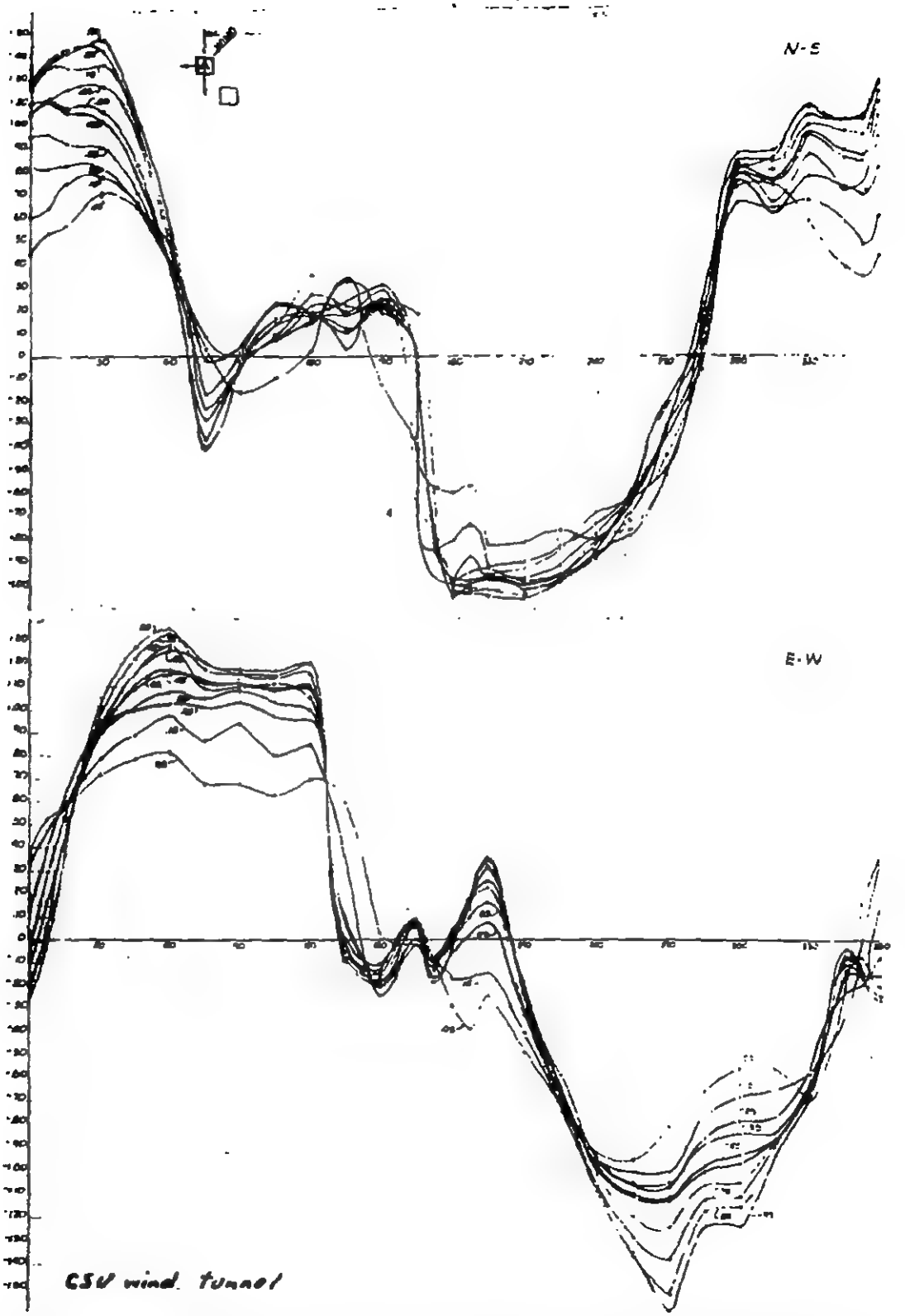

VARIATION OF FORCE COEFFICIENT FOR TOWER A WITH INCIDENCE FOR VARIOUS HEIGHTS ON THE TOWER (z/H)
NYSW TWIN TOWERS

FIG 42b

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Values of this function in different flow conditions are found to be in Table 4.

TABLE 4

	Model Configuration	$D(X)$	Approximate Value of $\frac{dC_{F_X}}{d\alpha}$
World Trade Center	Southeast Model of New York	-2.1	-2.2
	Southwest Model of New York	-1.71	-1.71
	Uniform Flow	-1.32	-1.33
Empire State Bldg.	Wide Face to Wind		- .85
	Narrow face to wind uniform flow		-1.60
Square cylinder			-2.66

Values of the derivative $\frac{dC_F}{d\alpha}$ for the square cylinder and the Empire State Building are given for comparison.

The aerodynamic damping integral for the twin towers in the SE and SW flows are shown in Fig. 43. Both flows are seen to give rise to qualitatively similar curves. Although aerodynamic damping is seen to be generally positive, regions do exist in which pronounced negative damping exists. Comparing these curves in Fig. 43 with the response curves in Figs. 16, 22, and 29, it is noted that large amplitude oscillations are to be found whenever the aerodynamic damping is negative. Exactly the same conclusion can be drawn for the single tower by comparing Fig. 40 and Fig. 13. This result is believed to be of considerable significance.

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FIG 43

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EXP 007004

Estimation of Peak Amplitudes*

It has been indicated by Davenport (1966) that an estimate of the response of a structure to turbulence can be made based on the knowledge of the spectrum of the turbulence and the mechanical properties of the system. To outline the procedure, the most simple case of the response of the tower to the uniform turbulence generated in the NPL wind tunnel is described. Other results are quoted later.

If the wind blows normal to the face of the structure, the spectrum of the generalized forces in the X and Y directions in a particular mode can be given in terms of the spectrum of velocity by the expressions

$$n\ S_{p_Y}(n) = \left[\frac{1}{2}\rho V_o^2\right]^2 \left\{4\ \bar{C}_{F_Y}{}^2 \left|J_Y(n)\right|^2 \frac{n\ S_u(n)}{\bar{V}^2} \int_0^2 \mu^2(z)\,dz\right\}^2 \tag{16}$$

$$n\ S_{p_X}(n) = \left[\frac{1}{2}\rho V_o^2\right]^2 \left\{\left|\frac{\overline{dC}_{F_X}}{d\alpha}\right|^2 \left|J_X(n)\right|^2 \frac{n\ S_v(n)}{\bar{V}^2} \int_0^1 \mu^2(z)\,dz\right\}^2 \tag{17}$$

where $n\ S_{p_Y}(n)$ and $n\ S_{p_X}(n)$ are the logarithmic spectra of the generalized forces in the Y and X directions and at frequency n, $\frac{1}{2}\rho V_o^2$ is the reference velocity pressure, $\bar{C}_{F_Y}$ and $\frac{\overline{dC}_{F_X}}{d\alpha}$ are effective aerodynamic coefficients,

*Theoretical results in this section are stated in more detail elsewhere (Davenport (1966).

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$|J_y(n)|^2$ and $|J_x(n)|^2$ are joint acceptance functions and are functions of the mode shape and vertical scale of the turbulence and $\frac{n\,S_u(n)}{\bar{V}^2}$, $\frac{n\,S_v(n)}{\bar{V}^2}$ are the logarithmic spectra of longitudinal velocity and of lateral velocity.

The root mean square fluctuation amplitude can be determined for a relatively lightly damped system by the expressions

$$\sigma^2(Y) = \frac{\pi}{4}\,\frac{1}{\delta_y}\left(\frac{dH}{k}\right)_y^2 n_o\, S_{p_Y}(n_o) \qquad (18)$$

$$\sigma^2(X) = \frac{\pi}{4}\,\frac{1}{\delta_x}\left(\frac{dH}{k}\right)_x^2 n_o\, S_{p_X}(n_o) \qquad (19)$$

where $\sigma(Y)$ and $\sigma(X)$ are the *RMS* amplitudes in the X and Y direction and δ_x and δ_y are the net critical damping ratios due to mechanical and aero-sources.

d is the tower diameter,

H is the tower height, and

k is the generalized stiffness for thet mode of vibration.

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Knowing the *RMS* amplitude, σ_Y and σ_X, the average peak amplitude during a period T can be found from the expression

$$Y_{peak} = \sigma_Y \sqrt{2 \log n_o T} + \frac{.57}{\sqrt{2 \log n_o T}} \qquad (20)$$

Choosing a period of 20 minutes, the peak amplitude is found to be

$$Y_{peak} = 3.25 \sigma_Y \qquad (21)$$

To calculate the response for the NPL model in uniform isotropic turbulence it is necessary to define certain quantities used in the above expressions.

The spectrum of turbulence for this flow is given in Fig. 10 of the NPL report. This result is replotted in Fig. 44. It should be noted that the longitudinal velocity component is plotted in Fig. 44. Since the flow is isotropic, the lateral velocity spectrum, required in determining the lateral response, is found from the fact that its ratio to the longitudinal spectrum is 4/3. This is confirmed by measurement shown in Fig. 44.

The joint acceptance function is computed from the expression

$$|J(n)|^2 = \int_0^1 \int_0^1 e^{-\frac{a|z-z'|}{\lambda}} \psi(z)\, \psi(z')\, dz\, dz' \qquad (22)$$

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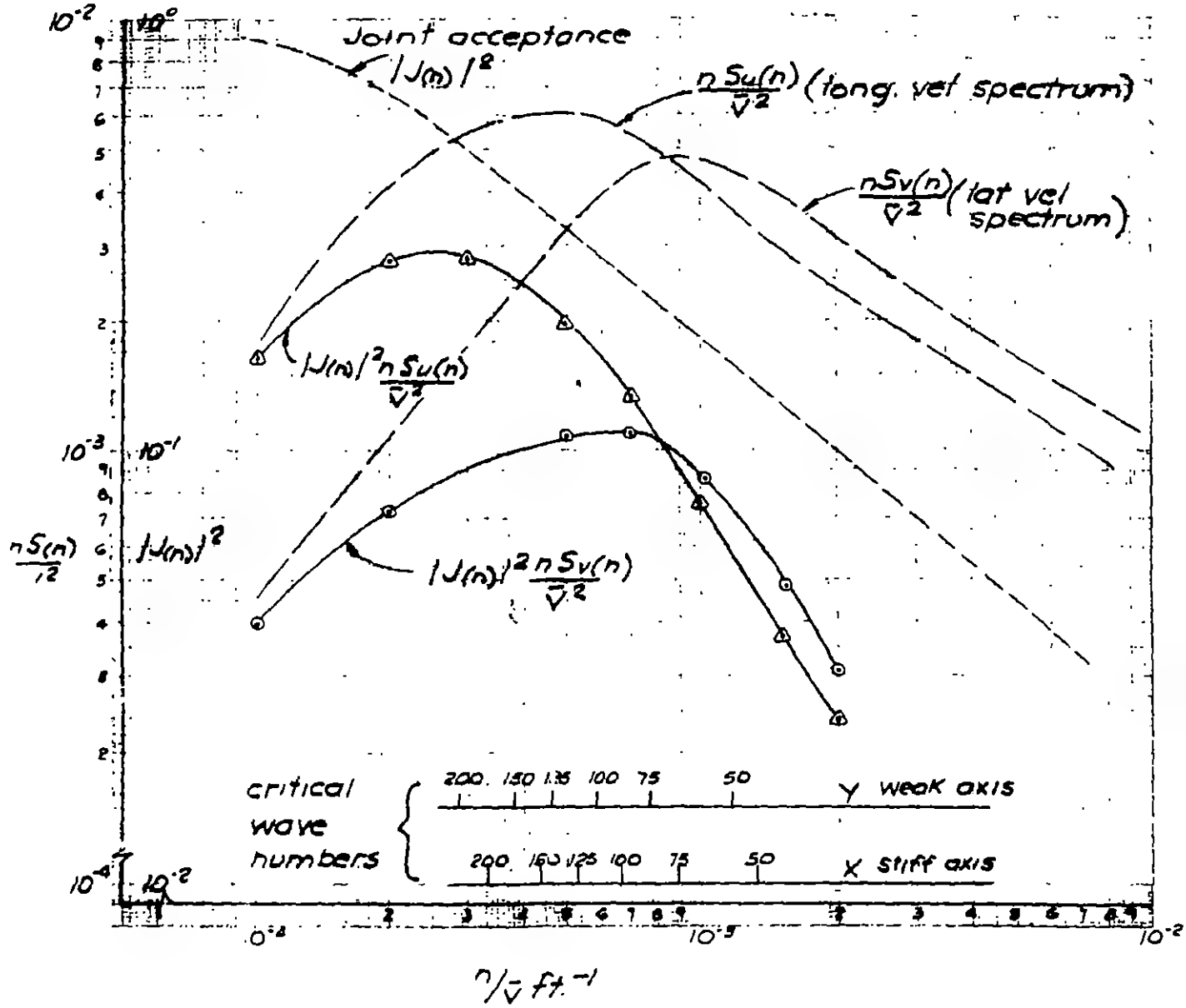
EXP 007007



CALCULATION OF FORCING SPECTRA DUE TO TURBULENCE (NPL TEST IN UNIFORM TURBULENT FLOW).

FIG 44

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EXP 007008

where $\mu(z)$ is the mode shape and λ the semi-scale of the turbulence at the particular wave length. Measurements by Vickery (1965) suggest that for this turbulence $\lambda = \frac{1}{7}\frac{\bar{V}}{n}$. The value of this joint acceptance function for different wave numbers $(n/\bar{V})$ is plotted in Fig. 44. The resulting spectrum of $|J(n)|^2 \frac{n\, S_V(n)}{\bar{V}^2}$ is also shown. This is required in computing equations (16) and (17).

The effective values of $\bar{C}_{F_Y}$ and $\frac{\overline{dC}_{F_X}}{d\alpha}$ were taken from CSU tests in uniform flow. While values of $\bar{C}_{F_Y}$ can be estimated with accuracy, values of the slope $\frac{\overline{dC}_{F_X}}{d\alpha}$ are less easy to obtain owing to the greater sensitivity of the slope to errors and the coarse spacing of the experimental points. The value of $\bar{C}_{F_Y}$ is approximately 1.4 while the value of $\frac{\overline{dC}_{F_X}}{d\alpha}$ was taken as -1.33 as suggested in Table 4 above. If Parkinson's accurate value for the infinite square cylinder of -2.80 is any indication, the latter value could easily have approached -2.0 close to the origin. The response for the latter case is also calculated.

The effective damping used in the equations is the algebraic sum of the mechanical and aerodynamic damping. That is

$$\gamma_{total} = \gamma_{mech} + \gamma_{aero} \qquad (23)$$

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The mechanical damping in this test was .012 and the aerodynamic damping was found from equations (7) and (8) (taking $\alpha = 0$) using the values of C_{F_Y} and $\frac{dC_{F_X}}{d\alpha}$ given above.

The resulting computed response curves are shown in Fig. 45 and compared with the experimental results. The theoretical and experimental results indicates two significant features. First, the variation of response with wind speed to be expected theoretically from turbulence excitation is qualitatively similar to that measured and second, the magnitudes of the agreement between the theoretical and experimental curves for the Y oscillation is reasonably close. In the X direction the calculated oscillations are less than half the observed. There are several possible explanations of the latter. One is that vortex shedding adds a significant contribution to the forcing function. This, however, would be expected to give rise to a peaked response at the critical wind velocity which is not evident in the observed response. The second is that the effective aerodynamic derivative $\frac{dC_{F_X}}{d\alpha}$ has been underestimated. Owing to the action of negative aerodynamic damping in this motion, the response level is highly sensitive to changes in $\frac{dC_{F_X}}{d\alpha}$. A 30% increase in this derivative would be adequate to double the predicted amplitudes and to bring them in line with the observed amplitudes.

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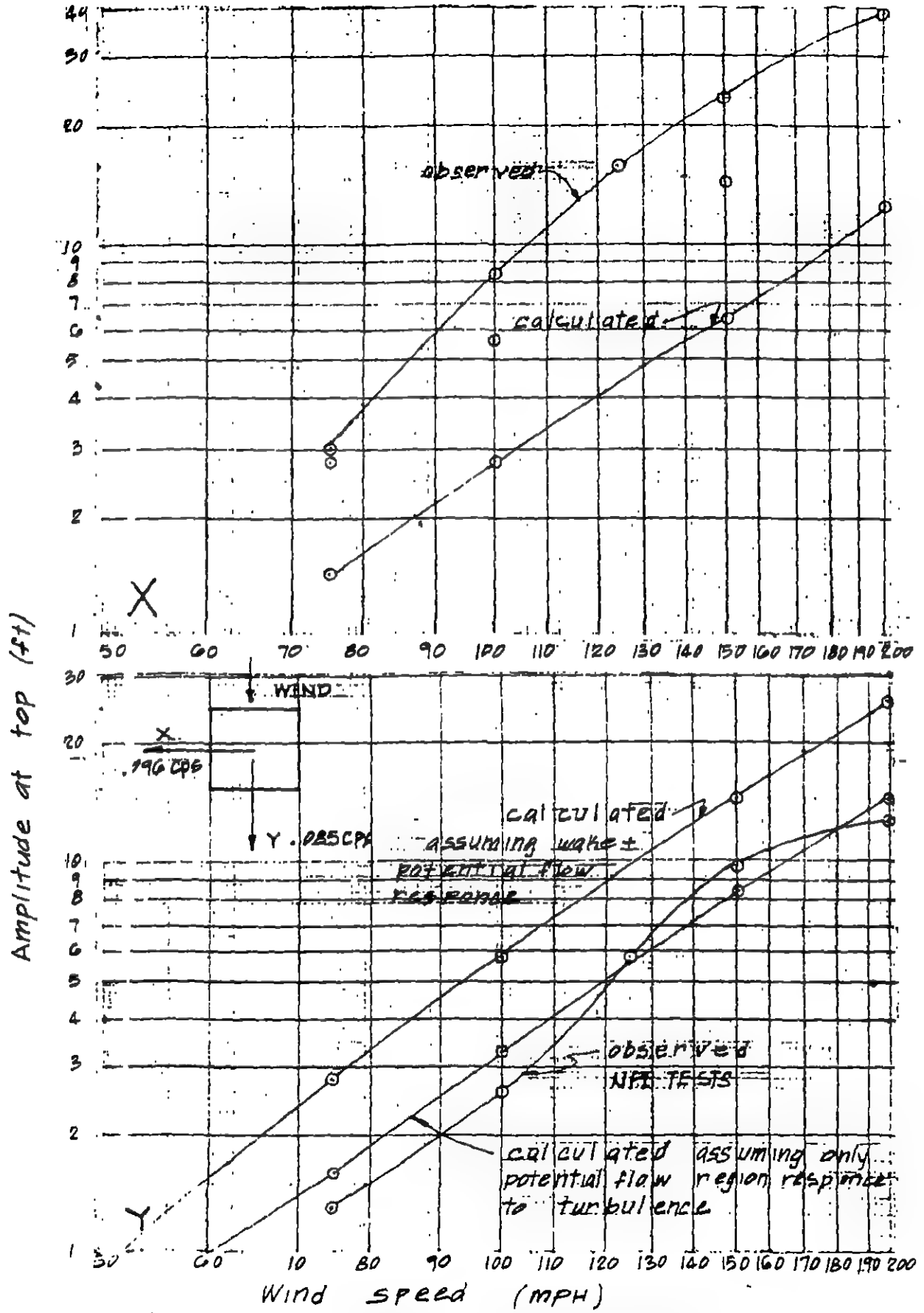
EXP 007010



COMPARISION OF PREDICTED OBSERVED RESPONSE OF SINGLE TOWER TO UNIFORM TURBULENT - 99

FIG 45

To extend these investigations further, the response of the single tower to the flow over the SE model of New York, measured in the CSU wind tunnel, were compared to theoretical predictions of the turbulence response based on measurements of the turbulence structure and based on the steady flow aerodynamic characteristics (given in Supplement Number 4). The turbulence spectra as measured on an analog spectrum analyzer are given in Fig. 79 in Part II of this report. Some of the results of this study are shown in Fig. 46 which are taken from the computer program given in Tables 5 - 8. Comparing with the observed results in Fig. 13, it is seen that the analytical results based on turbulence excitation alone gives a good qualitative and reasonable quantitative estimate of the measured response.

It is to be noted that for 1 percent mechanical damping, the tower becomes aerodynamically unstable at a wind speed approximately 180 mph.

According to the theoretical model presented above, it can be shown that the response can be reduced to the following form

$$\frac{\text{amplitude}}{\text{height}} \propto \left(\frac{\text{density air}}{\text{density building}}\right) \cdot \frac{1}{(\text{mech. damping} + \text{aero damping})^{\frac{1}{2}}} \cdot \left(\frac{V}{n_o D}\right)^2 f\left(\frac{V}{n_o D}\right) \cdot$$

$$(\text{effective aerodynamic coefficients}) \qquad (24)$$

In this relationship $f\left(\frac{V}{n_o D}\right)$ includes the composite normalized spectrum of the wind velocity and the joint acceptance of the particular mode. All terms are dimensionless.

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FIG 46

VARIATION OF MAXIMUM SWAY AMPLITUDE WITH WIND DIRECTION AND DEGREE OF DAMPING

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TABLE 7

ESTIMATE OF PEAK SWAY AMPLITUDE OF WORLD TRADE CENTER TOWERS

SOUTH-EASTERLY MODEL OF NEW YORK SINGLE TOWER

AZIMUTH ANGLE = 0.00 MODE = 1

N-S DIRECTION DAMPING INTEGRAL D(Y)= .755 COUPLING INTEGRAL C(Y)= 0.000

V MPH	REDUCED FREQUENCE	JOINT ACCEPTANCE		AERO-DAMPING	EXPECTED PEAK AMPLITUDES IN FEET FOR VALUES OF MECHANICAL DAMPING				
		LATERAL	LNGTUNL		.01	.02	.05	.10	.20
50	1.50E+00	0.00E-99	8.45E-04	2.53E-03	3.92E-01	2.95E-01	1.94E-01	1.39E-01	9.92E-02
75	1.04E+00	0.00E-99	1.17E-03	4.40E-03	1.16E+00	6.92E-01	5.97E-01	4.31E-01	3.08E-01
100	7.82E-01	0.00E-99	1.45E-03	5.87E-03	2.28E+00	1.78E+00	1.21E+00	8.83E-01	6.33E-01
125	6.25E-01	0.00E-99	1.68E-03	7.34E-03	3.64E+00	2.90E+00	2.00E+00	1.46E+00	1.05E+00
150	5.21E-01	0.00E-99	1.87E-03	8.80E-03	5.18E+00	4.18E+00	2.93E+00	2.15E+00	1.55E+00
175	4.47E-01	0.00E-99	2.04E-03	1.02E-02	6.83E+00	5.59E+00	3.96E+00	2.93E+00	2.12E+00
200	3.91E-01	0.00E-99	2.18E-03	1.17E-02	8.57E+00	7.09E+00	5.09E+00	3.78E+00	2.74E+00

E-W DIRECTION DAMPING INTEGRAL D(X)= -.686 COUPLING INTEGRAL C (X)= 0.000

50	1.76E+00	1.28E-03	0.00E-99	-2.21E-03	3.95E-01	2.61E-01	1.59E-01	1.11E-01	7.85E-02
75	1.17E+00	1.62E-03	0.00E-99	-3.32E-03	1.31E+00	8.30E-01	4.96E-01	3.44E-01	2.41E-01
100	8.43E-01	1.81E-03	0.00E-99	-4.43E-03	2.89E+00	1.73E+00	1.01E+00	6.99E-01	4.88E-01
125	7.00E-01	1.92E-03	0.00E-99	-5.53E-03	5.28E+00	2.92E+00	1.69E+00	1.14E+00	7.97E-01
150	5.89E-01	1.98E-03	0.00E-99	-6.64E-03	6.74E+00	4.38E+00	2.43E+00	1.65E+00	1.15E+00
175	5.04E-01	2.00E-03	0.00E-99	-7.75E-03	1.42E+01	6.09E+00	3.28E+00	2.22E+00	1.53E+00
200	4.41E-01	2.01E-03	0.00E-99	-8.86E-03	2.53E+01	9.09E+00	4.21E+00	2.93E+00	1.98E+00

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TABLE 6

ESTIMATE OF PEAK SWAY AMPLITUDE OF WORLD TRADE CENTER TOWERS

SOUTH-EASTERLY MODEL OF NEW YORK SINGLE TOWER

AZIMUTH ANGLE = 45.00 PAGE = 1

N-S DIRECTION DAMPING INTEGRAL D(Y)= .707 COUPLING INTEGRAL C(Y)= -.130

V MPH	REDUCED FREQUENCEY	JOINT ACCEPTANCE		AERO-DAMPING	EXPECTED PEAK AMPLITUDES IN FEET FOR VALUES OF MECHANICAL DAMPING				
		LATERAL	LNGTUNL		.01	.02	.05	.10	.20
50	1.56E+00	2.43E-04	5.56E-04	2.74E-03	3.70E-01	2.77E-01	1.81E-01	1.30E-01	9.28E-02
75	1.04E+00	3.28E-04	7.81E-04	4.12E-03	1.09E+00	8.40E-01	5.61E-01	4.04E-01	2.88E-01
100	7.82E-01	3.95E-04	9.75E-04	5.49E-03	2.16E+00	1.66E+00	1.14E+00	8.28E-01	5.93E-01
125	6.25E-01	4.49E-04	1.13E-03	6.87E-03	3.46E+00	2.74E+00	1.88E+00	1.37E+00	9.89E-01
150	5.21E-01	4.93E-04	1.27E-03	8.24E-03	4.93E+00	3.96E+00	2.76E+00	2.02E+00	1.46E+00
175	4.47E-01	5.29E-04	1.40E-03	9.61E-03	6.52E+00	5.30E+00	3.74E+00	2.75E+00	1.99E+00
200	3.91E-01	5.59E-04	1.50E-03	1.09E-02	8.19E+00	6.74E+00	4.80E+00	3.56E+00	2.59E+00

E-W DIRECTION DAMPING INTEGRAL D(X)= .707 COUPLING INTEGRAL C(X)= -.130

50	1.76E+00	2.20E-04	5.00E-04	2.28E-03	2.61E-01	1.94E-01	1.26E-01	9.06E-02	6.44E-02
75	1.17E+00	3.01E-04	7.08E-04	3.42E-03	8.11E-01	6.14E-01	4.06E-01	2.92E-01	2.08E-01
100	8.83E-01	3.66E-04	8.90E-04	4.56E-03	1.65E+00	1.27E+00	8.55E-01	6.17E-01	4.41E-01
125	7.06E-01	4.20E-04	1.04E-03	5.70E-03	2.72E+00	2.13E+00	1.44E+00	1.05E+00	7.53E-01
150	5.89E-01	4.64E-04	1.18E-03	6.84E-03	3.96E+00	3.13E+00	2.15E+00	1.57E+00	1.13E+00
175	5.04E-01	5.01E-04	1.30E-03	7.98E-03	5.31E+00	4.26E+00	2.96E+00	2.16E+00	1.56E+00
200	4.41E-01	5.31E-04	1.40E-03	9.12E-03	6.76E+00	5.47E+00	3.84E+00	2.83E+00	2.04E+00

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CIVIL AND STRUCTURAL ENGINEERS

TABLE 7

ESTIMATE OF PEAK SWAY AMPLITUDE OF WORLD TRADE CENTER TOWERS

SOUTH-EASTERLY MODEL OF NEW YORK SINGLE TOWER

AZIMUTH ANGLE = 0.00 DEGREE = 2

N-S DIRECTION DAMPING INTEGRAL D(Y)= 1.170 COUPLING INTEGRAL C(Y)= 0.000

V MPH	REDUCED FREQUENCEY	JOINT ACCEPTANCE		AERO-DAMPING	EXPECTED PEAK AMPLITUDES IN FEET FOR VALUES OF MECHANICAL DAMPING				
		LATERAL	LONGITUDINAL		.01	.02	.05	.10	.20
50	3.88E+00	0.00E-99	4.02E-04	4.54E-03	1.24E-02	9.60E-03	6.44E-03	4.65E-03	3.32E-03
75	2.58E+00	0.00E-99	5.48E-04	6.82E-03	4.30E-02	3.41E-02	2.34E-02	1.70E-02	1.22E-02
100	1.94E+00	0.00E-99	6.67E-04	9.09E-03	9.78E-02	7.93E-02	5.55E-02	4.09E-02	2.95E-02
125	1.55E+00	0.00E-99	7.58E-04	1.13E-02	1.76E-01	1.45E-01	1.04E-01	7.72E-02	5.60E-02
150	1.29E+00	0.00E-99	8.25E-04	1.36E-02	2.74E-01	2.30E-01	1.67E-01	1.25E-01	9.14E-02
175	1.10E+00	0.00E-99	8.73E-04	1.59E-02	3.88E-01	3.29E-01	2.43E-01	1.83E-01	1.34E-01
200	9.71E-01	0.00E-99	9.05E-04	1.81E-02	5.11E-01	4.39E-01	3.29E-01	2.49E-01	1.83E-01

E-W DIRECTION DAMPING INTEGRAL D(X)= .823 COUPLING INTEGRAL C(X)= 0.000

50	4.38E+00	9.39E-04	0.00E-99	2.65E-03	1.25E-02	9.36E-03	6.14E-03	4.39E-03	3.13E-03
75	2.92E+00	1.29E-03	0.00E-99	3.98E-03	4.49E-02	3.43E-02	2.29E-02	1.65E-02	1.17E-02
100	2.19E+00	1.61E-03	0.00E-99	5.31E-03	1.06E-01	8.31E-02	5.62E-02	4.07E-02	2.91E-02
125	1.75E+00	1.90E-03	0.00E-99	6.64E-03	2.02E-01	1.59E-01	1.09E-01	7.94E-02	5.73E-02
150	1.46E+00	2.17E-03	0.00E-99	7.96E-03	3.31E-01	2.65E-01	1.84E-01	1.35E-01	9.72E-02
175	1.25E+00	2.42E-03	0.00E-99	9.29E-03	4.91E-01	3.98E-01	2.80E-01	2.06E-01	1.49E-01
200	1.09E+00	2.65E-03	0.00E-99	1.06E-02	6.80E-01	5.56E-01	3.96E-01	2.93E-01	2.12E-01

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WORTHINGTON SKILLING HELLE AND JACKSON

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TABLE 8

ESTIMATE OF PEAK SWAY AMPLITUDE OF WORLD TRADE CENTER TOWERS

SOUTH-EASTERLY MODEL OF NEW YORK SINGLE TOWER

AZIMUTH ANGLE = 45.00 MODE = 2

N-S DIRECTION DAMPING INTEGRAL D(Y)= .892 COUPLING INTEGRAL C(Y)= -1.133

V MPH	REDUCED FREQUENCEY	JOINT ACCEPTANCE		AERO-DAMPING	EXPECTED PEAK AMPLITUDES IN FEET FOR VALUES OF MECHANICAL DAMPING				
		LATERAL	LNGTUNL		.01	.02	.05	.10	.20
50	3.88E+00	9.24E-05	4.67E-04	3.47E-03	1.49E-02	1.13E-02	7.52E-03	5.40E-03	3.85E-03
75	2.58E+00	1.23E-04	6.43E-04	5.20E-03	5.25E-02	4.07E-02	2.75E-02	1.99E-02	1.42E-02
100	1.94E+00	1.47E-04	7.90E-04	6.94E-03	1.20E-01	9.57E-02	6.58E-02	4.80E-02	3.45E-02
125	1.55E+00	1.67E-04	9.06E-04	8.67E-03	2.20E-01	1.77E-01	1.24E-01	9.12E-02	6.58E-02
150	1.29E+00	1.82E-04	9.95E-04	1.04E-02	3.46E-01	2.83E-01	2.01E-01	1.48E-01	1.07E-01
175	1.10E+00	1.96E-04	1.06E-03	1.21E-02	4.94E-01	4.10E-01	2.95E-01	2.15E-01	1.59E-01
200	9.71E-01	2.07E-04	1.11E-03	1.38E-02	6.57E-01	5.52E-01	4.02E-01	3.01E-01	2.19E-01

E-W DIRECTION DAMPING INTEGRAL D(X)= .892 COUPLING INTEGRAL C(X)= -1.13

50	4.38E+00	8.44E-05	4.23E-04	2.88E-03	1.03E-02	7.74E-03	5.09E-03	3.65E-03	2.60E-03
75	2.92E+00	1.13E-04	5.87E-04	4.32E-03	3.69E-02	2.63E-02	1.89E-02	1.37E-02	9.79E-03
100	2.19E+00	1.37E-04	7.27E-04	5.76E-03	8.72E-02	6.82E-02	4.63E-02	3.36E-02	2.41E-02
125	1.75E+00	1.56E-04	8.43E-04	7.20E-03	1.63E-01	1.29E-01	8.93E-02	6.52E-02	4.68E-02
150	1.46E+00	1.72E-04	9.37E-04	8.64E-03	2.62E-01	2.12E-01	1.48E-01	1.08E-01	7.85E-02
175	1.25E+00	1.85E-04	1.01E-03	1.00E-02	3.83E-01	3.13E-01	2.21E-01	1.63E-01	1.18E-01
200	1.09E+00	1.97E-04	1.06E-03	1.15E-02	5.19E-01	4.29E-01	3.07E-01	2.28E-01	1.65E-01

The aerodynamic damping is similarly expressed by the relation

$$\text{aerodynamic damping} = \frac{1}{\theta\pi} x \left(\frac{\text{density air}}{\text{density of building}}\right) x \left(\frac{V}{n_o D}\right) \text{effective aerodynamic coefficient} \quad (25)$$

A number of other studies which were carried out tended to support this general formulation of the response. The first of these studies concerns the dependence of response on the mechanical damping. Fig. 47 shows the variation of vibration amplitude as a function of the mechanical damping for the single tower with the southeast model of New York. The velocity is low enough for it to be believed that the aerodynamic damping is reasonably small compared to the mechanical damping. It is apparent from the log-log plot of amplitude versus damping (γ) that observations are in general in accordance with the relationship

$$\text{Amplitude} \propto \gamma^{-\frac{1}{2}}$$

as expressed in equation (24).

This approach can be applied to an examination of the aerodynamic damping. Fig. 48 shows a similar plot of amplitude versus damping for the data presented in Fig. 31 for various reduced velocities. If the general form of equation (24) is assumed, then the aerodynamic damping can be estimated from the difference between the total apparent damping and the actual mechanical damping of the system--as shown in Fig. 48. The aerodynamic damping estimated

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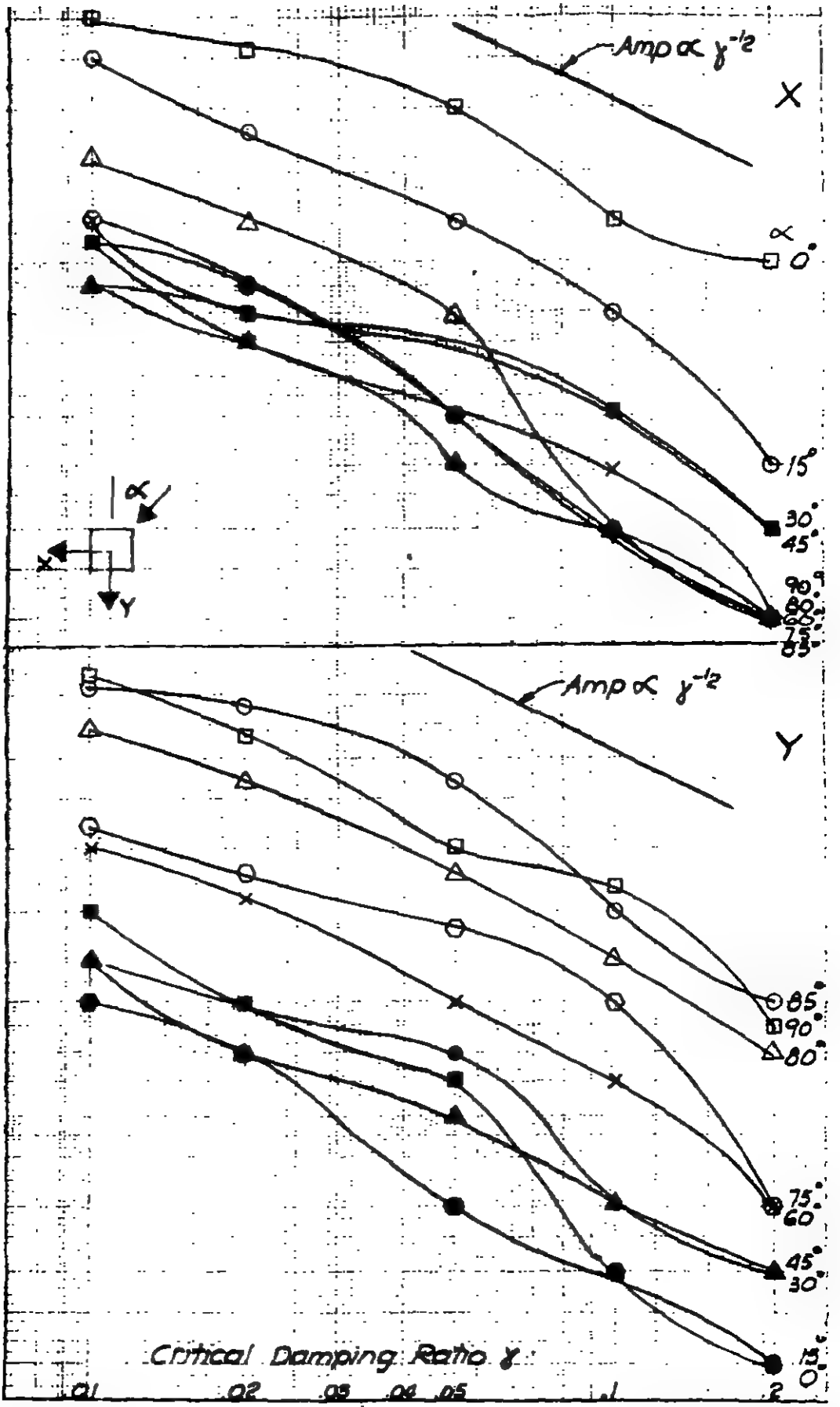

VARIATION OF PEAK AMPLITUDE OF OSCILLATION FIG. 97
WITH DAMPING - SINGLE TOWER - NYSE - V/nD = 8 (114 MPH)

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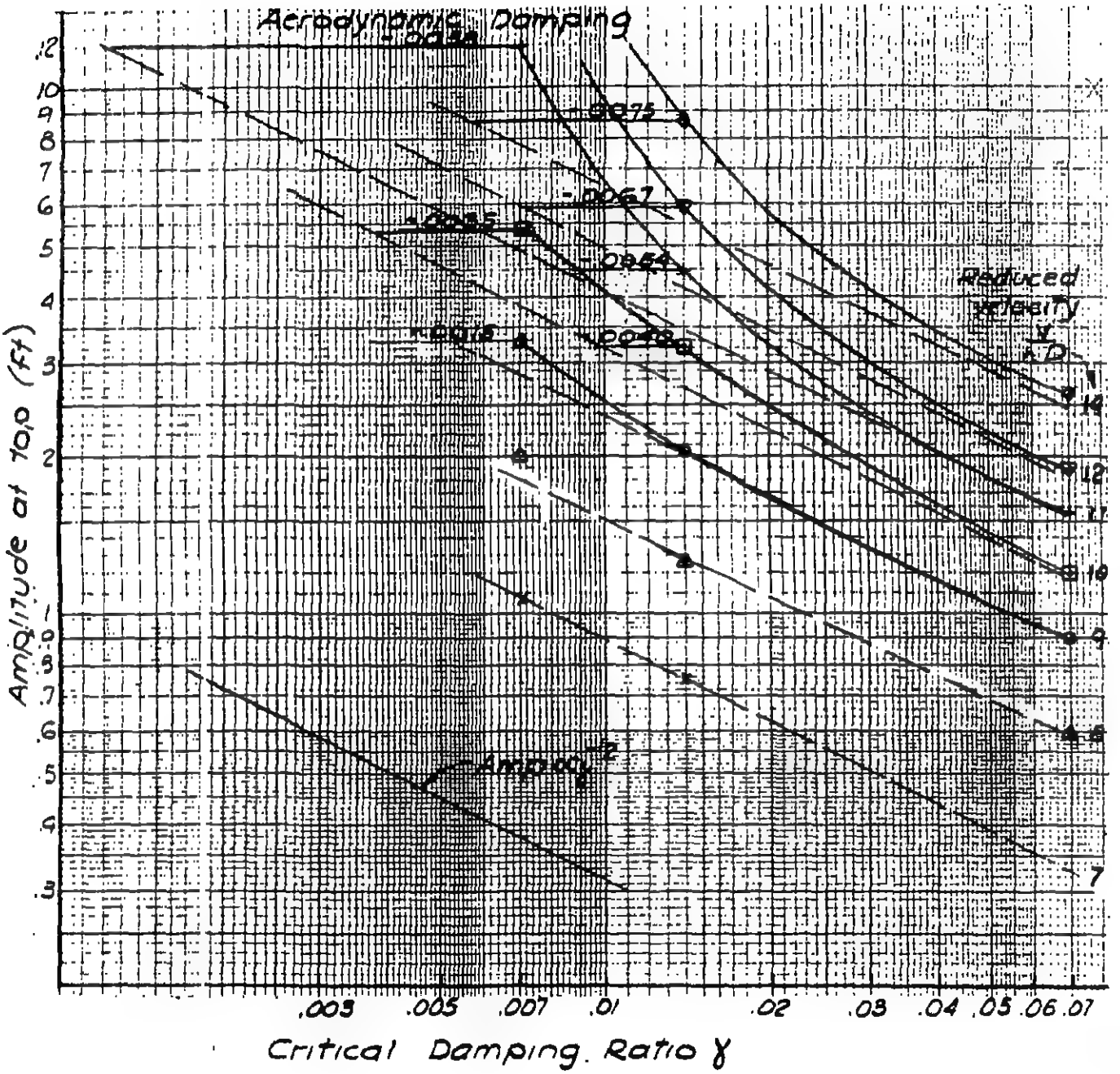

VARIATION OF AMPLITUDE WITH CRITICAL DAMPING RATIO FROM RESULTS FOR TWIN TOWER GIVEN IN FIG. 31

FIG 48

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from these results is plotted as a function of reduced velocity in Fig. 49. In all instances the aerodynamic damping is seen to be negative in accordance with the value of $D(Y)$ given for this direction ($\alpha = 90°$) in Fig. 43. It is seen that, although the quasi-steady approach does not appear to work at reduced velocities close to the eddy shedding velocity ($V/nD = 8$), there are indications that the quasi-steady form is approached at somewhat higher values.

This departure from the quasi-steady relationship is to be expected at lower reduced velocities. For example, at $V/nD = 1$, the body excutes one complete oscillation in the time taken for the flow to traverse the body from front to rear. This "communication log" in the flow renders it impossible for a quasi-steady flow regime, corresponding to the instantaneous motion of the body, to establish itself. As the flow velocity increases, so that the fluid travels a greater distance during oscillation, changes in the flow pattern due to the motion of the body are transmitted more rapidly and the quasi-steady situation is approached.

One other aspect that was considered was the value of so-called effective aerodynamic excitation coefficients, similar to the joint acceptance functions given in equations (16) and (17). Based on the quasi-steady approach these are related to the aerodynamic derivatives $\frac{dC_F}{d\alpha}$ and C_F and express the effectiveness of the turbulence in existing oscillations in any given mode.

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VARIATION OF AERODYNAMIC DAMPING WITH REDUCED VELOCITY FOR TWIN TOWERS. ESTIMATED FROM OBSERVED AMPLITUDES GIVEN IN FIG. 31

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FIG 40

These coefficients are plotted in Fig. 50. Their value indicates that high excitation might be expected in the north-south direction with the wind from 170°. In fact, it could be argued that slightly larger amplitudes are observed from this direction. On the whole, however, there does not seem to be a strong correlation between the excitation coefficients and the amplitude of oscillation. Certainly it does not approach the correlation between the occurrence of large amplitudes and the indication of negative aerodynamic damping.

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EFFECTIVE AERODYNAMIC EXCITATION COEFFICIENTS
NEW YORK SW TOWER A

FIG 50

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Comparison with Response of Empire State Building

There is some value in using equations (24) and (25) to relate the amplitudes to be expected on a single tower of The World Trade Center with those on the Empire State Building. Assuming that the Empire State Building can be regarded as a tower of similar general proportions to a tower of The World Trade Center and with an effective height of 85 stories (Observation Level) the ratio of the responses can be stated as:

$$\frac{amp_{ES}}{amp_{WTC}} = \frac{diam_{ES}}{diam_{WTC}} \cdot \frac{density_{WTC}}{density_{ES}} \cdot \left(\frac{damping_{WTC}}{damping_{ES}}\right)^{\frac{1}{4}} \cdot \frac{(V/n_o D)^2_{ES}}{(V/n_o D)^2_{WTC}} \cdot \frac{f_{ES}(V/n_o D)}{f_{WTC}(V/n_o D)} \cdot \frac{aero\ coeff_{ES}}{aero\ coeff_{WTC}}$$

From data available we have the following:

	Empire State Building	World Trade Center
Height	85 stories	110 stories
Density	17 lb/cu. ft.	10.5 lb/cu. ft.
Diameter	134 ft. (minor diameter)	208 ft.
Period	8.1 secs.	12.0 secs. (weak direction)
Damping	2-3% (assumed)	2-3% (assumed)

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From the velocity profiles in Manhattan it would appear that the velocities to which the Empire State Building is exposed are about 90% of those acting on The World Trade Center. The ratio of the reduced velocities is therefore

$$\frac{V_{ES}}{V_{WTC}} \cdot \frac{n_{o\ WTC}}{n_{o\ ES}} \cdot \frac{D_{WTC}}{D_{ES}} = .9 \cdot \frac{8.1}{12.0} \cdot \frac{208}{134} = .94$$

Comparison of the aerodynamic coefficients for the Empire State Building and The World Trade Center in uniform flow suggests these are similar and their ratio is, therefore, close to unity. Similarly, the aerodynamic excitation functions $f\left(\frac{V}{n_o D}\right)$ and damping values may be expected to be similar. Hence, the ratio of amplitudes is approximately

$$\frac{(amplitude)_{ES}}{(amplitude)_{WTC}} = \frac{134}{208} \cdot \frac{10.5}{17} \cdot (.94)^2 = .374$$

Colin Skinner, in a paper (Rathbun - 1940) discussing the effects of wind on the Empire State Building, reports that the single maximum sway amplitude of the Empire State Building, estimated from collimator readings, in an 80 mph wind (averaged over a minute or so) was approximately 3.6 inches. This implies that a single tower of The World Trade Center, situated in the site of the Empire State Building, might be expected to have a sway of approximately 9.5 inches. This value appears to be

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consistent with the CSU wind tunnel results which indicate a sway amplitude of about 14 inches for 3% damping for the southeast exposure which is, in all probability, a considerably more turbulent locality. The chances of observers being able to determine the absolute peak amplitude of the Empire State Building using their experimental procedure seem remote.

The ratio of the accelerations felt on The World Trade Center to those on The Empire State Building will be

$$\frac{1}{.374} \cdot \left(\frac{8.1}{12.0}\right)^2 = 1.15$$

Actual accelerations at the 3½ inch amplitude of the Empire State Building, deduced from measurements, are approximately 5.6 millig's.

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WORTHINGTON, SKILLING, HELLE & JACKSON
230 Park Avenue, New York, N. Y. 10017

TRANSMITTAL LETTER

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Ft. Collins, Colorado

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